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THE ACTIVE VOLCANOES OF NEW ZEALAND

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The northern island of New Zealand has, at the present time, five volcanoes which show more or less activity, besides a large number of others which have been active since Miocene time and are now dormant or extinct. This island has experienced much more volcanism during late geological time than the southern island, which consists largely of sedimentary and ancient metamorphic rocks. After traveling through North Island the writer was impressed by the simple statement of the Maori guide living near Mount Tarawera, who said, "New Zealand has been turned over and over."

The active volcanoes are White Island, in the Bay of Plenty, which displayed fresh activity in the autumn of 1914; Tarawera, near Rotorua, which suffered a terrific explosion in 1886; Ruapehu, which is in the solfataric stage and almost extinct; Ngauruhoe and Tongariro, which are in the solfataric stage, but still suffer explosive outbursts, those of Ngauruhoe being of considerable violence at times. The three last-named volcanoes are situated close together on the plateau in the central portion of the island.

There seems to be a close relationship among all these five volcanoes, as they are arranged along an almost direct line, indicating a zone of fissuring of immense proportions, known as the

Whakatane fault. Speight considers that this line continues from Ruapehu through Tonga and Samoa toward Hawaii along what he

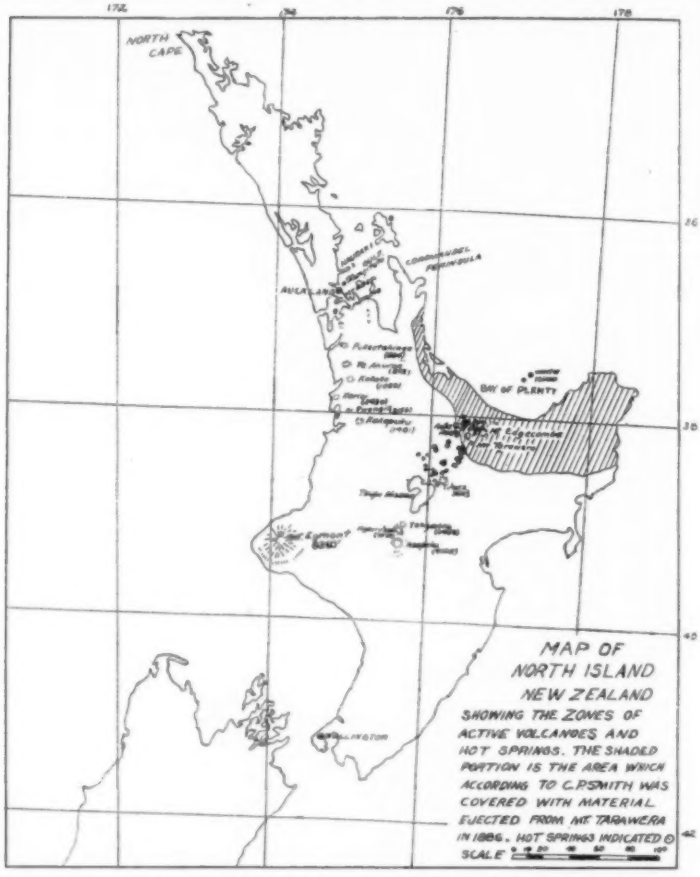

FIG. 1.—Map of North Island, New Zealand, showing the zones of active volcanoes.

calls the "Maori" line, since the Maoris probably migrated in a general direction along that line.[1] The "Samoan" and "Hawaiian"

[1] R. Speight, "Geology," *Report on a Bot. Sur. of the Tongariro National Park* (Dept. of Lands, N. Z., 1908), p. 9.

lines are supposed to cross the "Maori" line at their respective points of greatest volcanic activity. Running practically parallel to the fissured zone mentioned above, there is another zone containing numerous extinct or dormant volcanoes stretching along the eastern border of the island from the great Mount Egmont through the Auckland district, where over sixty craters, mostly of small magnitude, appear. There seem to have been, also, another line of disturbance and a great fault running from the north-central

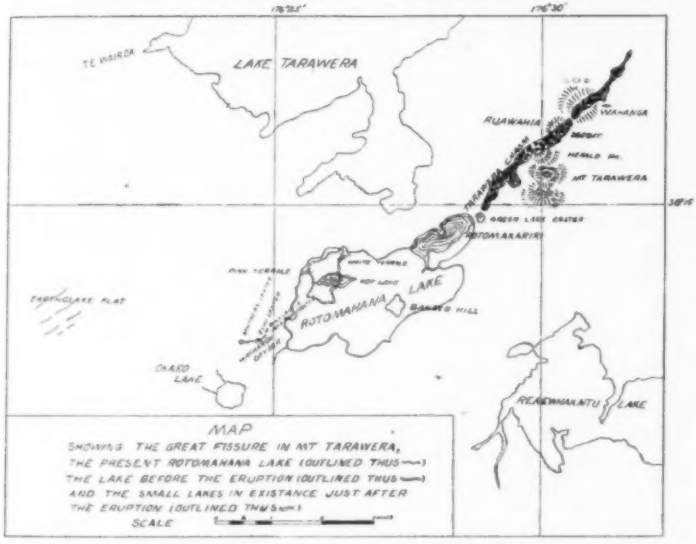

FIG. 2.—Map showing the course of the great fissure

part of the island nearly northwest to Hauraki Gulf and passing through the Waihi mining district. The prominent scarp of this fault may be seen from Morrinsville Junction in going from Auckland to Rotorua, and it is necessary to ascend this steep slope to reach the plateau before arriving at Rotorua. The streams descend rapidly over this scarp, which is a prominent physiographic feature of the landscape. This *graben* fault has aided in producing the lowland stretching from Hauraki Gulf toward the central portion of the island.

These major zones of disturbance run parallel to the main structural features of the islands resulting from the orogenic and epirogenic movements which produced New Zealand and the adjacent islands.

HISTORY OF THE LATER VOLCANIC ACTIVITY OF NEW ZEALAND

There seems to be a general agreement among New Zealand geologists that there were extensive post-Jurassic and pre-Mioeene movements, resulting in much folding and in bringing the islands nearly to their present geographical condition. The rocks formed up to this time indicate, according to Marshall,[1] that the present islands occupied a zone along the border of a continent now lost to sight. The folding raised the mountain ranges from the sea bottom and determined the major structures of the islands. There have been numerous oscillations since that time, but these have not materially altered the main structural features. Following these great disturbances, which may be correlated with those of America and Europe, there was inaugurated an important stage of igneous activity which became very prominent in the Miocene and has continued, more or less actively, since that time. There was some igneous activity during the Jurassic, and even then hypersthene-andesites, so common in later periods, began to make their appearance. Igneous rocks of this age are found, according to Park,[2] in the Hauraki Peninsula, while the andesites and rhyolites of the Canterbury district in South Island are regarded by some geologists as Jurassic.

The greatest period of activity seems to have opened in the Middle or Lower Miocene and to have extended into the Pliocene, and even into the Recent, in North Island. During the Miocene, which was also characterized by extensive orogenic and epirogenic movements, the main centers of activity were the Otago, Banks, and Hauraki peninsulas. The rocks of these areas generally rest on Omaru sediments, which are regarded as Early Miocene. In the Otago Peninsula the alkaline rocks were erupted at this time; in the Banks Peninsula, rhyolite, andesite, and basalt; and in the

[1] P. Marshall, *Geology of New Zealand* (Wellington, N. Z., 1912), p. 188.

[2] James Park, *The Geology of New Zealand* (Whitcombe & Tombs), p. 82.

Hauraki Peninsula, andesites followed by rhyolites. Probably the andesites extending north of Auckland up to North Cape were contemporaneous with those mentioned. The important gold veins of the Waihi mines are connected with this period of eruption as a later phase of the activity.

The great volcanic plateau occupying the central portion of North Island consists largely of rhyolite and pumice with the later extrusions of andesite and related rocks breaking through the rhyolites. The first evidence of the activity which produced the plateau is found in the rhyolite gravels of the Miocene, but the main eruptions are believed to be of Pliocene age because much of the pumice is found resting on early Pliocene strata and some is interbedded with them. The earliest igneous rocks of this plateau are, therefore, rhyolite and the latest andesite. As to the source of these acid rocks, there are factors which point to the Taupo area as the center of the eruption. While the writer did not have the opportunity of visiting Lake Taupo, he is convinced, after visiting other lakes in this region and reading descriptions of the Taupo basin, that these larger lakes in the central portion of the island are old craters modified by faulting. There is so much in common between such depressions and many of those of crater origin in the Hawaiian Islands that their origin can scarcely be in doubt.

The early andesite eruptions of Ruapehu, Tongariro, Egmont, Edgecombe, and related volcanoes occurred in the Pliocene, while the basanites of the Auckland area are probably of Pleistocene age.

PETROGRAPHICAL PROVINCES IN NEW ZEALAND

There is such a close relationship between the rocks of the Ruapehu–White Island and Egmont-Auckland zones that they may be justly regarded as belonging to one province. The rocks of Mount Egmont consist of hornblende-andesite and hornblende-augite-andesite; those of the Auckland region of basanite, poor in nepheline and probably lacking in this mineral in some cases; those of Ruapehu of augite-hypersthene-andesite; and those of White Island of hypersthene-andesite.

On the Coromandel Peninsula there were first eruptions of andesites of various types followed by rhyolite and these again by

hypersthene-andesite. It is probable that the great rhyolite extrusions of the central plateau were contemporaneous with those of the Coromandel Peninsula, and that the early andesite extrusions of this region did not occur in the plateau area. There are dacites in both areas.

Park considers that there are two other petrographic provinces in New Zealand of late Miocene or early Pliocene age, these being found on the Otago and Banks peninsulas.[1] In the former peninsula the rocks consist of an earlier series of phonolite, dolerite, trachydolerite, andesite, basalt, and basanite; and a later series, erupted on the eroded surface of the first, consisting of basalt with probably andesite and phonolite. Cutting the lavas of the first series are dikes of nephelite-syenite, augite-dolerite, and tinguaite. Professor Marshall, who has made a detailed study of this area, states that no regular order of eruption and no definite system of differentiation in these various rocks have, so far, been recognized.

On Banks Peninsula there was a period of rhyolite eruption followed, after considerable erosion, by andesites and basalts.

From the evidence presented there does not seem to be any regular order of eruption followed by rocks of the various types, except that in practically all cases there is a tendency for the volcanism to cease with the eruption of intermediate rocks, as andesites.

RUAPEHU, NGAURUHOE, AND TONGARIRO

These three large volcanoes are located near the center of North Island at the southern end of the rhyolite plateau. Their craters lie along a direct line, within a distance of less than fifteen miles, and if this line be projected northeastward it will pass also through Pihanga and Tauhara, volcanoes now extinct; then through Tarawera, Edgecombe, and White Island. Ngauruhoe is situated between the other two and almost on the side of Tongariro, in such a way as to indicate that it has arisen in the later stages of Tongariro as a subsidiary cone to this great volcano.

The rocks of all three of these volcanoes are similar, and consist of augite-andesite with augite-hypersthene-andesite. The early activity produced extensive flows of these rocks followed by

[1] Park, *op. cit.*, p. 147.

alternating lava flows and fragmental deposits of the same material. Ruapehu has not been in active eruption since early in the Recent period, but Ngauruhoe and Tongariro continue to suffer regularly weak outbursts. Evidence of this may be seen in Fig. 6. According to Marshall there has not been a flow of lava from a New Zealand volcano in historic times, but Park and Speight believe that in 1869 a lava flow escaped from the northwest side of Ngauruhoe and that the fresh appearance of this lava attests its recent origin.

FIG. 3.—Ruapehu (9,175 feet) from the Waiouru-Tokaanu road eight miles distant. Looking across the Onetapu Desert covered with volcanic sand and cinders.

Ruapehu.—This is an enormous mass of red to dark-gray lava and scoriae rising from a plateau region. Its height has been placed by various writers at 8,878 feet to 9,175 feet above sea-level, and the latter may be considered as the more correct figure. It has a large crater, approximately a mile in diameter, cut into on the south-southeast side by a great ravine, so that the rim of the crater consists of a series of prominent peaks. The crater is occupied by a glacier which surrounds a small, hot lake said to be about 600 feet in diameter. According to various reports, the water sometimes boils, and apparently it is the sulphur water from this lake which issues from the northeast side of the mountain.

The writer was unable to reach the lake on the date of his visit in October, 1914, owing to the steepness of the ice walls between the point where he reached the crater and the location of the lake, and from the brink of the crater no sign of it could be seen in the snow field within the crater.

The sides of the cone are covered with masses of andesite from the disintegrated lava flows and with fragments of large bombs. In some cases columnar structure is well developed in these flows.

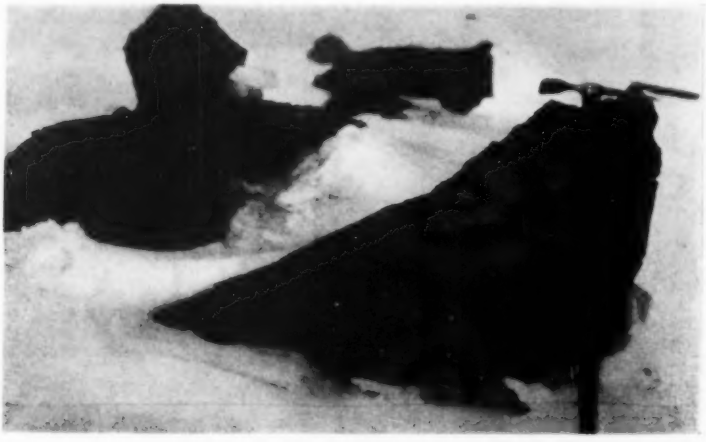

FIG. 4.—Bread-crust structure in a portion of a large bomb near the foot of Ruapehu.

In a fragment of a large bomb lying near the foot of the mountain and almost buried in the snow and cinders, an excellent example of bread-crust structure was found (Fig. 4). Small glaciers hang on the cone, extending, in some cases, as low as 2,000 feet below the crater rim.

Ngauruhoe.—This is a beautiful and symmetrical cone resting on an upland base which was probably largely developed by Tongariro before Ngauruhoe was of much importance. The elevation of this mountain is placed at 7,481 feet by S. P. Smith, and at 7,515 feet by Marshall. It is made up of a base of andesite flows on which rests the cone, consisting of alternating lava flows

and beds of tuff and agglomerate, with bowlders up to ten feet in diameter. Some interesting examples of flows which appear to have split, passing above and below beds of agglomerate and tuff,

FIG. 5.—Ngauruhoe from a point near the foot of Ruapehu. This view shows how the cone is built on an upland largely developed by Tongariro.

FIG. 6.—Ngauruhoe (7,515 feet) showing the usual cloud of steam and sulphur fumes rising from the crater.

may be seen on the east side of the cone (Fig. 7). These are found, on close examination, to be due to the viscous lava piling up and becoming brecciated in movement, so as to resemble a bed of tuff and agglomerate.

There was considerable snow and ice on the mountain when the writer visited it in the spring season, early in October, but this disappears in the summer and no glaciers remain here, as on Ruapehu.

FIG. 7.—Apparent splitting of lava flows. This seems to be due to the viscous lava becoming brecciated in movement so that it resembles tuff and agglomerate. The liquid lava then flows over the fractured layer.

The crater may be entered on the north side, where the rim is broken away and it is comparatively level on the bottom except for two mud volcanoes on the floor and a deep depression on the west side, the depth of which cannot be estimated since it is always full of fumes. The diameter of the main crater is about 500 feet and the height of the perpendicular walls on three sides of it was estimated at 200 feet in the higher portions. In the small crater there is a great deal of activity. Large clouds of steam mingled with sulphur dioxide rise continuously, and at times detonations like the crack of heavy rifle-fire may be heard. Considerable dust is intermittently shot up from this crater and, as seen from Fig. 8,

these explosions are occasionally quite violent. The explosion which threw out the cloud seen in the photograph, and which occurred on October 3, 1914, was said by some of the residents of Waiouru, twenty-five miles distant, who witnessed it, to be one of the strongest outbursts observed for at least two years. Up to the time this occurred, on the date mentioned, no sign of activity was seen around the mountain top, until at 9:30 A.M. this cloud was suddenly shot up about 1,000 feet before being drifted away

FIG. 8.—Cloud of dust and steam blown from Ngauruhoe, October 3, 1914. This explosion was much more violent than usual.

by a terrific wind, which was blowing at the time and prevented the cloud from rising to a great height.

Fumaroles occur around the steep walls of the main crater and well down the north side of the cone. On the northeast side of the cone was seen some reddish, highly vesicular, ropy lava, which has every appearance of being quite recent. As mentioned above, it has been stated by a number of writers that this stream was erupted in the year 1869, but not all New Zealand geologists are in accord on this subject.

Tongariro.—There are many features which make it appear that Ruapehu and Tongariro are major volcanoes with Ngauruhoe

subsidiary to the latter. Tongariro is an immense volcano, but with a cone of much less altitude than that of either of the others just described. The history of this mountain has been very

FIG. 9.—Looking from Ngauruhoe into the center of the crater of Tongariro and showing the Red Crater in the foreground.

FIG. 10.—One of the later flows of andesite from Ngauruhoe

similar to that of Ruapehu. According to all the descriptions given, the lavas are andesites, mostly of the augite-hypersthene type, with small amounts of the hornblende-hypersthene type in some of the earlier flows. The cone consists of alternating lava flows and beds of scoriae. According to Speight[1] the height of the cone was greatly reduced by a terrific explosion, which was followed by extensive lava flows, and which blew 2,000 to 3,000 feet off the mountain. The crater rim now has a maximum altitude of 6,458 feet and is made up of a number of peaks surrounding several minor craters. One of these, known as the Red Crater because of the red color of the lava, is situated near the center of the main crater. Another, called Te Mari, lies on the northeast corner, and a third known as Tama is southeast of Ngauruhoe. Tama is believed to be part of the old crater rim, even if it lies beyond Ngauruhoe, and this is proof of the subsidiary character of the latter crater. All these craters are in the solfataric stage, but Te Mari is said by Speight to suffer explosive activity at times and to throw out ashes and stones. It was from this crater that the flow of andesite poured down through the forest on the flank of the mountain, and the conditions indicate that this eruption occurred at a comparatively recent date, although not within historic time.

In a depression on the main crater floor there is a small lake, called Blue Lake, lying at an elevation of about 5,500 feet. This lake, Te Mari, Red Crater, and Ngauruhoe all lie in almost a straight line, and they are apparently located on a fissure, or narrow zone of weakness, in the earth's crust. The Ketetahi Hot Springs are situated a little to the east of the line mentioned and well down on the northern flank of the mountain. They exhibit very strong thermal activity. Lying between Ngauruhoe and Ruapehu there are two small lakes, which probably owe their origin to some of the explosive activities of Tongariro.

MOUNT TARAWERA

Much has been written on Tarawera but many of the original works are out of print and unavailable. Reports have been prepared for the government bureaus of New Zealand by A. P. W.

[1] Speight, *op. cit.*, p. 11.

Thomas, Sir James Hector, and S. P. Smith, while other descriptions may be found in the works of Hutton,[1] Marshall,[2] and Park.[3] The special interest in this volcano lies in the great eruption of 1886, which produced results of much scientific, economic, and humanistic importance. The opening of the yawning chasm through the mountain, followed by the distribution of ashes over thousands of square miles of country with the accompanying destruction of life and property, is a matter of interest to every traveler who approaches this region.

Mount Tarawera was a small, nearly flat-topped mountain of rhyolite about 3,600 feet high and approximately 2,500 feet above Lake Tarawera lying at its base. There are on the mountain three prominences, known as Wahanga, Ruawahia, and Tarawera, the latter giving its name to the mountain as a whole. The structure was that of almost horizontal beds of pumice and flows of rhyolite, which had been poured out of some adjacent volcano or fissure, and which made up part of the rhyolite plateau in the central portion of North Island. Up to the time of the great explosion there was no evidence of a crater in the mountain, but it is situated in the zone of fissuring which runs from Ruapehu to White Island, and previous to the eruption there were numerous hot springs and geysers in the vicinity of the present Lake Rotomahana. It is close to Lake Tarawera, which has every appearance of being an old crater modified by local subsidence. The walls are steep and the water near the shore is deep in many places. The same condition exists in Lake Taupo and it may be concluded that all the steep-walled lakes in this region are of crater origin. The whole region lying between Tarawera and Rotorua is perforated with craters, hot springs, and geysers.

THE ERUPTION OF 1886

During the night of June 10, 1886, violent rumblings were heard and minor earthquakes experienced in the region surrounding the mountain. These increased in violence until about 2:00 A.M., when

[1] F. W. Hutton, *Report on the Tarawera Volcanic District*, Wellington, 1887. Also "The Eruption of Mount Tarawera," *Quar. Jour. Geol. Soc.*, XLIII, 1887.

[2] Marshall, *op. cit.*, p. 107. [3] Park, *op. cit.*, p. 166.

the main eruption commenced and the great fissure began to open in the mountain, commencing at the north end in the hump called Wahanga. It passed through Ruawahia toward the basin now occupied by Lake Rotomahana and formerly containing the small lakes, Rotomahana and Rotomakariri. It opened under the lakes about 2:30 A.M. with a terrific roar and a cloud of steam which rose over 15,000 feet high.[1] This no doubt was due to the water rushing into the heated zone and producing a great explosion of steam. The result was the opening of a large pit, now occupied by Lake Rotomahana, while the débris was scattered widely over the country. The finer materials were carried out to sea over the Bay of Plenty, as indicated on the accompanying map (Fig. 1). It has been estimated that from the great fissure from 520,000,000 to 620,000,000 cubic yards of material was thrown out and this was spread over an area of almost 6,000 square miles, of which 1,500 square miles were damaged more or less severely from the agricultural standpoint. All habitations within four miles of the mountain were destroyed and 116 people killed. Most of these were natives, and while the majority of them were killed by the falling materials burying them, some around Rotomahana, where the natives often gathered, were literally carried away by the explosion. At Te Wairoa the buildings were crushed in and all vegetation destroyed or very severely damaged. There is still very little vegetation near the mountain, but it is interesting to see how quickly it has re-established itself at Te Wairoa, where the eucalypti are already fourteen to fifteen inches in diameter and other trees of less rapid growth are eight inches. The fern, like the braken of this country, establishes itself very quickly and flourishes on the acid soil. In many places the charred remains of trees are found, not only in the ashes of this eruption, but also in the ashes of earlier date.

The main eruption lasted about five hours, although the more violent part was probably over in less than an hour. Earthquakes continued for many days and there seems to have been some unusual activity in the hot springs around Rotorua. There have also

[1] According to S. P. Smith the measured height was 15,400 feet. "The Eruption of Tarawera," *A Report to the Surveyor-General*, New Zealand, 1887.

been reports of sympathetic action in Ruapehu, White Island, and other places along the volcanic zone.

Previous to the eruption of Mount Tarawera there were numerous hot springs and geysers in the area occupied by the present Lake Rotomahana, and the famous Pink and White sinter terraces were situated well within the border of the present lake.

THE GREAT FISSURE

As stated above, the eruption of Mount Tarawera began at the northern end of the mountain and progressed southward with the opening of an enormous fissure. This chasm is about $8\frac{3}{4}$ miles long, $1\frac{1}{4}$ miles wide in Lake Rotomahana, and 900 feet deep in the mountain. It is one of the most extraordinary openings to be found anywhere in the earth's crust (Fig. 11). Where it cuts through the mountain it takes the form of several deep, narrow craters in linear succession, separated by wedges of rock not blown out by the great explosions. The deepest opening is about 900 feet and it is about 1,000 feet wide at this point. In some places the crater walls are nearly vertical, but in others they have a gentle slope and can be descended to the bottom. There are a few small fumaroles, but they are no longer important. Along the brink of the chasm there is about 175 feet of highly colored, red and variegated scoriae deposited on top of the rhyolite materials thrown out of the fissure, but there is no evidence of a lava flow.

The fissure runs down the mountain side and through Lake Rotomahana, where it is 520 feet deep and has very steep walls in some places. It reached its maximum width here, where it is $1\frac{1}{4}$ to $1\frac{1}{2}$ miles wide. The present lake is about 4 miles long and 2 miles wide, and it covers the areas formerly occupied by the old Lake Rotomahana and Lake Rotomakariri. In the fissure, immediately after the eruption, there was a small lake called Hot Lake, but gradually the whole depression became filled with water. The explosion completely destroyed the Pink and White sinter terraces, which were located within the present basin rim, and fragments of them may be picked up for miles around where they are mingled with the other ejectementa from the fissure. There is still much thermal activity around Rotomahana, the name of which

FIG. 11.—The great fissure through Mount Tarawera. *A*, the north end; *B*, deep central portion; *C*, looking down fissure to Lake Rotomahana. In *A* and *B* the layer of red scoriae is distinctly seen along the brink of the fissure with the lighter rhyolite underlying it.

signifies "warm lake," and steam rises from many parts of the shore, especially near the northwest corner where the terraces and other hot-spring phenomena were most prominent before the eruption. The color of the water is a sort of dirty, greenish gray, like that of glacial streams, this hue being caused, no doubt, by the large amount of extremely fine particles of mineral matter suspended in the water.

Continuing westward the fissure passes through Black, Inferno, Echo, and Southern craters, all of which exhibit considerable

FIG. 12.—Lake Rotomahana, through which the great fissure passes from end to end. Looking westward from Mount Tarawera.

thermal activity at the present day. The basin of the extraordinary Waimangu Geyser, now inactive, is located on this line a short distance from Lake Rotomahana. This geyser became active in 1900 and continued more or less irregularly until 1908, when it ceased to act. It has been reported by various reputable authorities that it often threw water and mud to a height of from 1,200 to 1,500 feet. With the extinction of this geyser the surrounding springs became more active. The Waimangu "blow hole," situated southwest of the geyser orifice, blows hot water and steam for two minutes and is then quiescent for seven. In Echo Crater

the floor and walls are dotted with hot springs and fumaroles, and around some of these springs a great deal of iron pyrite is being deposited on pebbles, particularly in a spring called "The Frying Pan." The pyrite becomes disseminated in the sinter and to some extent it impregnates the thermally altered rhyolite. It seems to owe its origin to the reaction between H_2S and some iron salt, which in all probability is the chloride. The sulphide coats the pebbles with a black, smooth, waterworn layer which later tends to assume more nearly the appearance of typical pyrite. An assay was run on this pyrite deposit to determine the presence or absence of gold, and no trace of gold or silver was found. It seems probable that the pyrite in the sinters around Rotorua is of the same origin, and the large deposits of sulphur around the springs near Lake Rotorua appear to be due to the oxidation in the air of the H_2S so plentiful in these waters.

While the great fissure practically ends at the Southern Crater there are some smaller fissures and faults in Earthquake Flats which indicate the extension of the disturbance beyond the main fissure. There are lines of former movement which were again depressed a few feet.

DETAILED DESCRIPTION OF THE ROCKS OF MOUNT TARAWERA

This mountain was originally made up of interbedded rhyolite and rhyolite pumice, with streaks of dark gray to black, spherulitic obsidian running through the rhyolite. The bands often have the appearance of irregular dikes in the rhyolite, but they are probably due to the varying rate of cooling in different parts of the flows. The dark obsidian contains many fragments of the lighter rhyolite, and in some cases these have the appearance of being partly absorbed. This may be explained by the rhyolite fracturing on the cooled surface, permitting the liquid beneath to pour out around the brecciated fragments and to cool quickly. Good examples of this spherulitic obsidian were found on the road leading from Te Wairoa down to the landing on Lake Tarawera. Fragments may also be picked up among the débris from Tarawera, showing that the rock exists in the deeper beds in the mountain.

The rhyolite is quite fresh, brittle, and friable. Thin sections show that it contains a very deep dark-brown biotite, some augite, and, in one case, a grain of hypersthene, in addition to orthoclase, albite, and quartz which is very glassy and brilliant. The groundmass is usually mostly glass.

The obsidian consists of a brittle, dense, black glass, showing flow structure. It is full of spherulites from 0.05 mm. to 3.5 mm. in diameter. The glass contains also phenocrysts of green hornblende, orthoclase, and zonally built crystals of orthoclase and albite. The smaller spherulites consist of radiating needles of feldspar, while the larger ones are nearly solid glass around the center, with radiating dark lines and with concentric spheres

FIG. 13.—Bombs of andesite and basalt from Mount Tarawera. In two of them the light-gray cores of rhyolite may be seen (½ natural size).

becoming more distinct toward the exterior. These spheres are alternately brown and gray. The outer thick zone is brown and shows only a glass without crystal structure. The other zones show radiating small crystals of feldspar under the high-power microscope, but there is so little crystal structure that only a very slight darkening and brightening can be observed on rotating the section between crossed nicols, and there is almost no difference in birefringence between the spherulite and the surrounding glass. A distinct bending of the microlites in the glass around small spherulites may often be observed.

Bombs.—During the eruption of 1886 a considerable amount of intermediate to basic rock was ejected from the crater. It has been estimated that from 520,000,000 to 620,000,000 cubic yards of material was blown out of the great fissure. This was largely

rhyolite, but about 175 feet of dark, reddish-brown scoriae consisting of ashes, lapilli, and bowlders of vesicular and ropy lava lies along the brink of the great chasm through Mount Tarawera. The lava, which was the last to fall on the mountain, except some material from the basin of Rotomahana, welled up beneath the chasm and was caught in the big explosion. It was blown to fragments and thin layers of the fine material are mixed with the lighter colored tuff from the rhyolites around Rotomahana. It formed irregular masses of scoriaceous and ropy lava up to two feet in length, while it quite frequently formed spherical and oval bombs (Fig. 13). These bombs occur in great numbers around the foot of the mountain. The most peculiar are those with a core of rhyolite and an enveloping coat of andesite or basalt. They owe their origin to the fact that fragments of rhyolite were engulfed in the more basic lava, and when the explosion occurred these were hurled into the atmosphere with a rotary motion so that the viscous molten material became well wrapped around the core of solid rock. As a rule, this core is not exposed until the bomb is broken open. They all show the bread-crust structure well developed owing to the shrinking of the cooling, molten coat around the solid interior. In the specimens examined there is a sharp line of contact between the two rocks and there is no evidence of fusion of the rhyolite.

An examination of thin sections of the more basic rock showed in one case much dark, grayish-brown, vesicular glass containing numerous little laths of feldspar, a little augite, and a few small phenocrysts of enstatite. In another specimen the same minerals were found, with the exception of augite. In one small bomb the feldspars were identified from their extinction angles as anorthite and bytownite, and this same specimen contained traces of quartz, possibly due to absorption of some of the acid rhyolitic material before ejection. It was carefully examined for nephelite, owing to the reported occurrence of nephelite in the Auckland lavas, but it was found to be optically positive and to lack any sign of cleavage. Very small crystals of augite were present. The rock is a quartz basalt.

Dr. Marshall mentions hypersthene-augite-andesite in the bombs from Mount Tarawera,[1] but no hypersthene has been found

[1] Marshall, *op. cit.*, p. 102.

by the writer, the orthorhombic pyroxene in all cases being like enstatite.

From the description given it is evident that these rocks vary from andesite to basalt and that they represent a much more basic phase than any rocks previously erupted in the vicinity of Mount Tarawera. The sequence is very similar to that in all the other volcanoes in this petrographic province.

GLACIATION IN THE VOLCANIC ZONE

There has been much discussion in New Zealand in recent years regarding glaciation in North Island. Outside of the comparatively small glaciers on Ruapehu the writer did not see any evidence of glaciation. Around both Ngauruhoe and Ruapehu there were many bowlders which had grooves very similar to those often made by glaciers. It was surprising to find, however, that in practically all cases these were not due to glaciation, but probably to the action of one mass of rock falling on another when hurled from the craters. This was proved by the fact that the groove would often end abruptly against the wall in a re-entrant angle in such a way that it could not have been produced by glacial action.

FOOTHILLS STRUCTURE IN NORTHERN COLORADO

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INTRODUCTION

The area under discussion comprises a part of the foothills of the "Front Range" of Colorado, west and north of Denver, and extends from Morrison about 70 miles north to Fort Collins. No attempt will be made to discuss the stratigraphy of this district nor to describe any of the geological formations in detail; only the structural features will be emphasized.

STRUCTURAL FEATURES

THE FOOTHILLS MONOCLINE

The "master structural feature" of the foothills has been well described by Fenneman[1] in his discussion of the geology of the Boulder district, and also by Eldridge in the monograph on the

[1] *U.S. Geol. Survey Bulletin 265*, 1905, pp. 41–43.

geology of the Denver basin.[1] The following description is taken from the latter publication:

> The normal appearance of the foothills is that of a mountain mass of Archean rocks, fringed at an average distance of one half or three quarters of a mile by a sharp serrated ridge of Dakota sandstone, the valley between the two being occupied by the formations of the Trias and Jura. Above the Dakota come . . . . the Benton, the Niobrara—this generally constituting a second smaller reef outside the Dakota—the Pierre, the Fox Hills, and the Laramie, the basal sandstones of the Laramie again forming either a low roll in the ground or an actual comb of rock slightly projecting above the surface of the surrounding prairie. To the east of the Laramie . . . . appears in the southern portion of the area yet another comb formed by the conglomerates at the base of the Arapahoe series. Finally this is followed by . . . . the Denver formations.

To this description it is well to add that as a general rule the Lyons formation forms a prominent, though low, hogback in the strike valley to the west of the Dakota, and that in the northern part of the foothills the Archean-Fountain contact forms a prominent strike valley, and that here the Fountain is characteristically developed into a high, precipitous hogback, usually capped on its crest and dip slopes by the Lyons sandstone. Here also the Arapahoe and Denver formations are absent, and the Laramie lies almost horizontal twenty miles or more to the east of the foothills. In the southern part of the area the dips in the Fountain, Lyons, and Lykens average from 35° to 50°. These increase gradually eastward until they become vertical or even overturned in the Laramie, dips as low as 75° west being noted. Farther eastward these flatten within a few hundred feet from vertical into practically horizontal in the upper part of the Arapahoe or the base of the Denver.

No such variation is noted in the northern part of the area under discussion. West of Loveland dips of 40° are rare and occur only locally as the result of special conditions. The steepest dips occur here in the Dakota or Morrison. It is also worth noting that in the southern part of the area, where steep and overturned dips are met with, the formations have turned practically horizontal within two miles of the Archean contact—in one extreme

[1] *U.S. Geol. Survey, Monographs*, XXVII, 1896.

case (at Golden) even within 4,500 feet from the contact; while in the northern part of the area dips of 15° east are found as much as 10 miles east of the Archean sedimentary contact.

These contrasts in dips indicate that the foothills fold differs in shape and intensity over this area. The generally low dips near Fort Collins and Loveland indicate an ideal, fairly gentle, monoclinal fold, while the steep and overturned dips to the south indicate an S-shaped fold of pronounced type. The fold proper is well described by Fenneman[1] as follows:

> The master structural feature of this region is the great upturn of the strata against the mountain range. . . . . The first Archean belt west of the foothills is a dissected plateau . . . . from 6,500 to 7,000 feet above sea-level at its eastern edge, where it ends abruptly and is flanked by the Fountain sandstone. . . . . The height . . . . above the plains is nearly 1,000 feet. . . . . Five miles east of the base of the foothills the Archean surface is at least 9,500 feet below the surface, or 4,200 feet below the level of the sea. The real face of the granite plateau is therefore about 2 miles high, and this enormous rise is accomplished in 6 miles.

The opinion is also expressed that the greater part of the monoclinal flexure is the result of subsidence during the deposition of the various sedimentary formations, a conclusion passed on the assumption that the ancient shore line was located along the line of the present Front Range.

This generalization was, however, based on a small area of the foothills in which the characteristic structure is not well developed. Further, Lee[2] has proved since that all the Cretaceous formations up to and including the Laramie formerly were continuous over the present site of the Front Range. Consequently their present attitude must be due to orogenic forces, and the statement that "the process of mountain making gave to the granite plateau west of the foothills a comparatively small relative uplift above the plains" is erroneous.

A careful study of the dips and strikes of the formation south of the Boulder area and the reconstruction of a fold based on these dips as well as the occurrence of the lower formations as "inliers"

[1] *Op. cit.*, pp. 41, 42.

[2] *U. S. Geol. Survey*, P.P. 95-C.

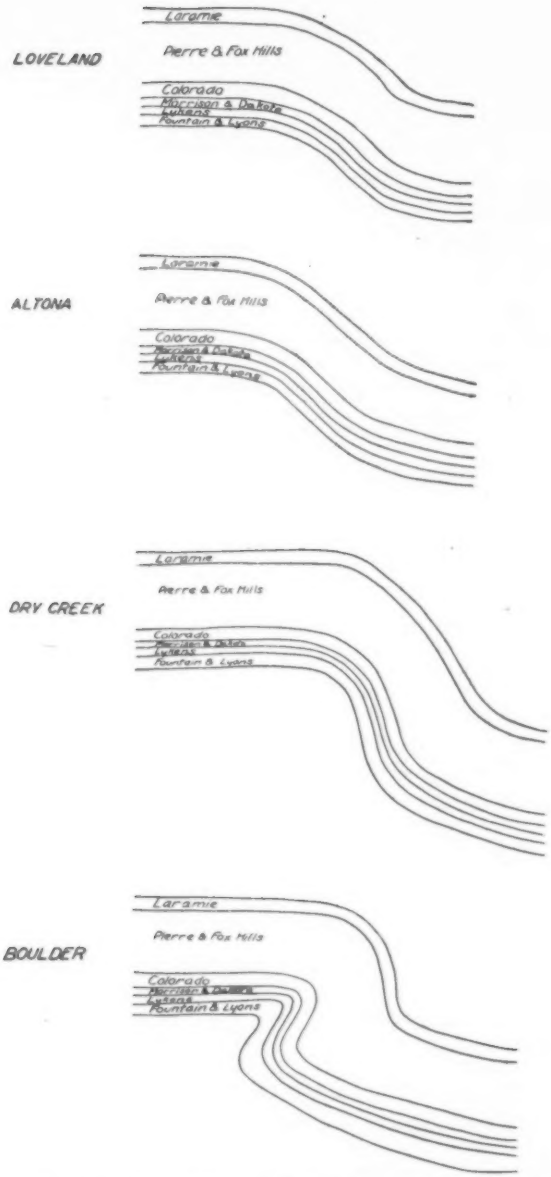

FIG. 1a.—Reconstructions of the original monoclinal fold of the foothills of the Colorado Front Range.

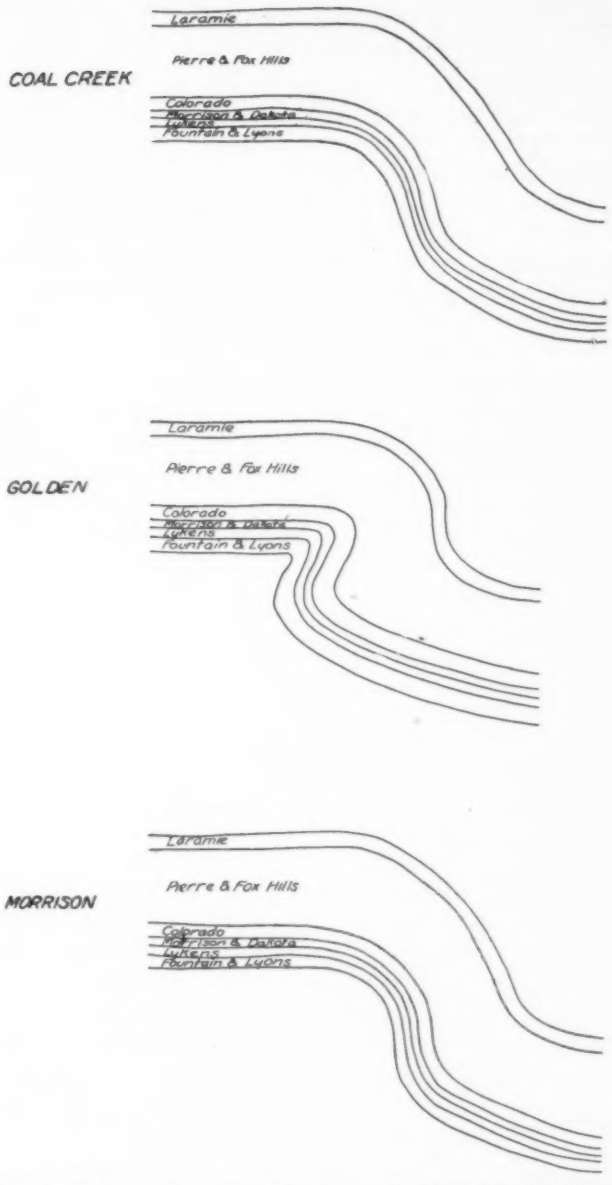

FIG. 1*b*.—Reconstructions of the original monoclinal fold of the foothills of the Colorado Front Range.

in the Archean some distance west of the foothills, as for example west of Colorado Springs and also west of Loveland, furnishes good reasons for the belief that the formations underlying the Dakota also extended over the Archean, or at least for a considerable distance westward. In areas undisturbed by special local conditions, the Fountain, Lyons, Lykens, and Morrison show as close an agreement in dips and strikes with the overlying formations as would be expected for conformable rock series; and all show beautiful parallelism in folding with the younger rocks. This would be a rather peculiar coincidence, not to be expected except in rocks simultaneously folded.

The accompanying diagrams show, drawn approximately to scale, reconstructions of the original monoclinal fold worked out from dips and strikes at the localities noted. In each case faults and other local irregularities which would unnecessarily complicate the fold have not been indicated. Their possible effect, due to displacements of parts of the fold and consequent introduction of anomalous dips and strikes, has been carefully considered in each case, and, where necessary, corrections have been made in the flexure of the monocline. These reconstructions are merely intended to show the variation in the shape and curvature of the foothills monocline in its major outlines (Fig. 1, *a*, *b*, pp. 718–19).

It is interesting to note that in older interpretations of the monoclinal fold in this region the overturn is located underneath the surface and not above the surface, as the present writer has drawn it. Considering no more than the present dip and strike relationship along an east-west line at such localities as Golden or Boulder, and considering these to be located on the same horizontal plane on the monoclinal fold, no other logical interpretation is possible. If, however, the variations in dip be carefully plotted along the axis of the fold, and if we carry in mind the fact that the dips as observed at Golden and Boulder represent different horizontal planes on the monocline due to the disappearance of thousands of feet of strata, the type of overturn postulated by the writer becomes necessary in order to explain observed conditions. This will perhaps be clearer after a discussion of the structure at Golden.

LOCAL UNCONFORMITIES (SO-CALLED "ARCHES")

Certain peculiarities in the distribution of the geological formations along the foothills, especially well developed near Golden and Boulder, have been explained as the result of unconformities due to local arching in the Cretaceous sea.

The Golden area.—The sketch map of the vicinity of Golden is, with a single correction, the map by Eldridge given in his report on "The Geology of the Denver Basin."[1] The areal distribution of the formation has been well traced in this map and has proved essentially correct, while the general features of the area in question (Fig. 2) have been well described in the following words:[2]

> The topography shows a marked variation from that normal for the foothills region in general. . . . . For mile after mile along the mountains the normal topographical features may be traced with unswerving regularity, but within the area to be described they undergo rapid change, and . . . . in the vicinity of the town of Golden they are lost to recognition. For a distance of over a mile north of the town, and an equal distance south of it, the Dakota hogbacks have completely disappeared; the low Niobrara ridges cease to exist at a point about a mile north of Bear Creek, not to appear again until the region of Van Bibber Creek, 10 miles to the north, is reached; the Laramie sandstones with their coal have gradually approached to within 500 feet of the Archean at Clear Creek, the variation in their strike from that of the Triassic and Dakota outcrops below being apparent to the most casual observer. . . . . The lines of stratification are delineated clearly upon the surface and display a distinct tendency to group themselves, with respect to direction, into two well-marked assemblages—the one embracing the formations of the Colorado and all below, and maintaining for the greater part of their extent the same parallelism to the general trend of the foothills which they have held beyond the affected area; the other embracing the Montana and younger formations, and though maintaining a parallelism of strike within themselves, nevertheless abutting against the older formations, in fact approaching the range proper in a broad, well-marked, and regular inward-sweeping curve, the center of its arch lying a short distance north of Clear Creek. The features just noticed again occur, in a minor degree and in a manner not at first liable to attract attention, in the relations between the Dakota and underlying beds nearer the middle of the area, where the beds of the younger formation lie across the edges of those of the older.

[1] *Op. cit.*, p. 83.

[2] *Op. cit.*, pp. 83–84.

Eldridge discusses each geological formation in great detail, and the care with which all structural features are described is worthy of special note. Rather than cite at length from this report the writer has arranged the pertinent data given in tabular form.[1]

STRUCTURAL FEATURES AT GOLDEN

Permo-Trias (Fountain, Lyons, Lykens)

1. Rapid disappearance of strata successively from the top downward as they approach Golden. Lyons disappears 1 mile north of Clear Creek, and ½-mile south respectively. Lykens disappears about two miles north and south of Clear Creek.
2. Disappearance of Lykens is sudden north of Clear Creek; gradual to the south.
3. Discrepancy of 10° in strike with upper formations on disturbed area.
4. Normal thickness of Morrison is present where much of Lykens is missing.

Morrison

1. Missing for a distance of about 1¼ miles.
2. Discrepancy in strike (10°–15°) with younger Dakota and older rocks on disturbed area—especially marked in part north of Clear Creek.
3. Sudden disappearance of Morrison north of Clear Creek; gradual disappearance south.

Dakota and Purgatoire

1. Disappears from bottom up and top down.
2. Discrepancies in strike with rocks above and below on disturbed area.
3. More sudden disappearance on north side of area.
4. Marked crumpling on north side—frequent changes in strike, not shown by Laramie, which is only 600 feet to the east.
5. Normal dip 45°. Dips 90° and overturned over disturbed area.
6. Remarkable crumpling and recumbent folding south of Golden. (Not noted by Eldridge.)

Benton and Niobrara

1. Completely disappear from top downward. Benton absent for distance of about 5 miles; Niobrara for 9 miles.
2. Conformable in dip and strike to Dakota, but not to Montana on disturbed area.
3. After disappearance of Niobrara, overlain by successively higher Montana beds as it approaches Golden.

[1] *Op. cit.*, pp. 91–97.

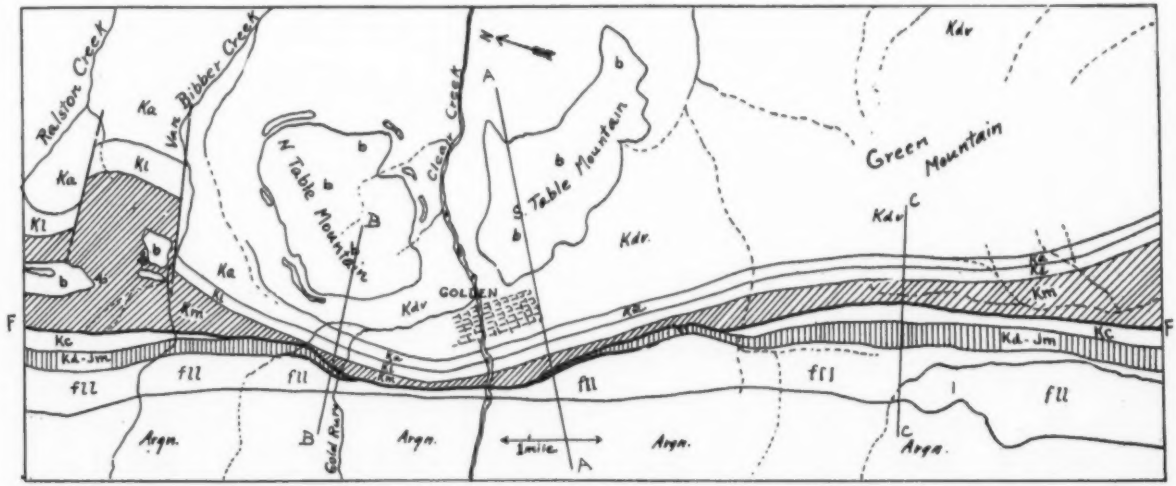

FIG. 2.—Sketch map of the vicinity of Golden. Heavy lines show faults

Argn	= Archean	*Km*	= Montana (Fox Hills and Pierre)
fll	= Fountain, Lyons, and Lykens	*Kl*	= Laramie
Kd-Jm	= Morrison, Dakota and Purgatoire	*Ka*	= Arapahoe
Kc	= Colorado (Benton and Niobrara)	*Kdv*	= Denver

Montana (Pierre, Fox Hills)

1. Pierre completely disappears from bottom upward. Absent for distance of about 4½ miles. Upper part of Fox Hills, only present at Golden.
2. Conformable in dip and strike to Laramie. Shows a discrepancy of 15°–20° in strike with older rocks.
3. Steepest dips on area at Golden—90° and overturned (80° W).

Laramie

1. Broad, sweeping curve by which it is gradually carried to the westward until at Golden it lies within 4,500 feet of the Archean.
2. No thinning.

ELDRIDGE'S HYPOTHESIS OF AN "ARCH" AT GOLDEN

The abnormal conditions tabulated above are all explained as the result of a series of unconformities at the horizons where these occur.

There is postulated a headland of anticlinal structure with axis perpendicular to the present trend of the foothills. This has been named the "Golden Arch" (Fig. 3). No attempt will be made to discuss the so-called "arch hypothesis" in detail. For such, the reader is referred to previous publications.[1] It will be noticed that the lines along which certain formations disappear are roughly parallel to the general strike of the foothills formations; and that as we approach Golden the formation to the west of such a line—that is, the older—disappears from the top down; while the formation to the east—that is, the younger—disappears from the bottom up. In the "arch hypothesis" such disappearance is explained as the result of the erosion of the older formations from the top of the rising headland, followed by a subsidence and a gradual overlapping of the younger formations against the sides and eventually over the top of this arch. The older formations are missing because of erosion; the younger, because of non-deposition.

Comments on the Arch Hypothesis: A number of points brought out in a former discussion as well as some additional data from field work seem to show serious weakness in the arch hypothesis. These points are in part facts described in detail by Eldridge and summarized above, in part facts discovered since, or at least not specifically noted by him, and in part certain fundamental

[1] *U.S. Geol. Survey, Monographs* (1896), XXVII, 91–97.

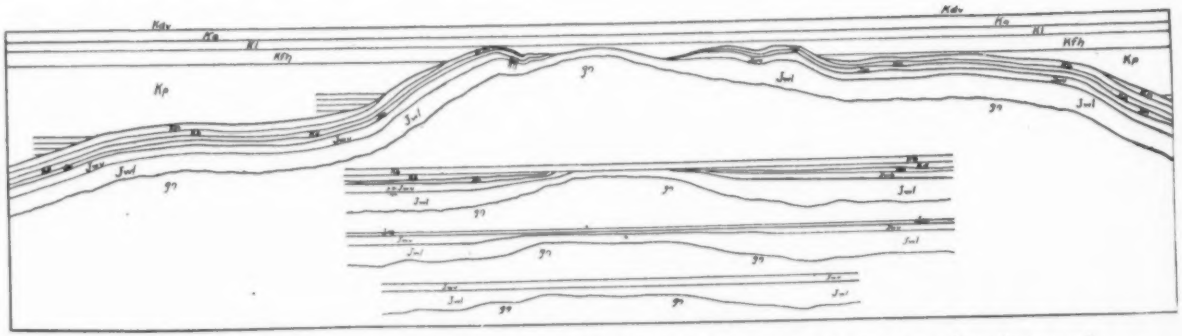

FIG. 3.—Stages in the development of the Golden arch (after Eldridge). Stages 1, 2, 3, and 4 are shown (from bottom up)

gn	=Archean	*Kn*	=Niobrara
Jwl	=Fountain and Lyons (Lower Wyoming)	*Kp*	=Pierre
Jww	=Lykens (Upper Wyoming)	*Kfh*	=Fox Hills
Jm	=Morrison	*Kl*	=Laramie
Kd	=Dakota (and Purgatoire)	*Ka*	=Arapahoe
Kb	=Benton	*Kdv*	=Denver

assumptions that appear unsound or at least unwarranted to the writer. The chief objections may be summarized as follows:

I. Objections based on facts:

1. The steepest dips occur where the formations disappear. For what reason, if their disappearance be due to an unconformity?

2. The greatest amount of overturning (60° W) is where the greatest thickness of strata is missing. The same question may be asked as for point No. 1.

3. Crumpling is common along the lines of the supposed unconformities.[1] Why?

4. Crumpling is relatively more severe on the axis of the supposed arch, that is, on the line where the greatest thickness of rock is missing. Why?

5. Crumpling is relatively more intense at those points where the formations disappear suddenly. Why this coincidence if their disappearance be due to erosion or non-deposition?

6. There is a remarkable coincidence of an association of maximum divergence of strike lines, steep and overturned dips, maximum crumpling, and the sudden disappearance of a formation. The simultaneous relationship of these to an unconformity is not clear.

7. There is an absence of shore facies in the sedimentaries. The existence of the Golden arch presupposes the existence of shore conditions, but none of the formations supposedly deposited against this arch show any change in lithological character upon crossing or approaching it.

8. No similar structures have been recognized elsewhere in the Rockies.

9. On the bluffs immediately to the south of Clear Creek the Dakota shows a dip of 60° westward, while less than 100 feet west the Fountain shows a dip of 40° eastward. These dips cannot be explained on the basis of an unconformity. (Not noted by Eldridge.)

[1] See also H. B. Patton, "Faults in the Dakota Formation at Golden, Colorado," *Colo. School of Mines Bulletin*, III, No. 1 (1905), pp. 26–32. A complete overturn through 180° is here described.

10. There are many minor strike thrust faults clearly shown, as well as dip faults with steep fault planes and a hingelike displacement toward the east—all of which are most pronounced in the immediate vicinity of Golden.

II. Objections based on interpretation:

11. The arch hypothesis presupposes the existence of a shore line immediately to the west. The work of Lee[1] has proved the former extension of the Cretaceous formations in a continuous sheet across the entire area of the Front Range. Hence this whole area must have been an epicontinental sea, and consequently a "headland" similar to the arch could not have been present at Golden.

12. Too much oscillation required of a small local area. Such rapid alternations of up and down movements are a strain on credulity.

13. It seems incredible that an elevation sufficient to prevent the deposition of any Pierre shale could have taken place at Golden, while a few miles to the north and south the true thickness of the Pierre (7,700 feet according to Eldridge) was deposited.

14. Another weak point in the arch hypothesis is the present attitude of the strata. These if considered in the plane of their bedding form a syncline with east-west axis over the crest of the supposed arch. The limbs on each side are dipping inward as much as 35°. None of the strata show any evidence of the original anticlinal folding to which they must have been subjected in order to form the "arch." A simple calculation will show that the arch requires an anticline with average dips of at least 10° in the older rocks for 10 miles north and south of Golden, while in the crest of the arch the dips must have risen as high as 30°. Eldridge, Emmons, and Fenneman are therefore driven to the conclusion that this arch was flattened out probably in Denver time and distorted into its present shape. This requires the sudden conversion of a persistently and rapidly rising area into a remarkably rapidly subsiding one, and requires a bending in the strata similar to that of a card bent back and forth between the fingers. This whole reasoning is not only laborious but also illogical.

[1] *Op. cit.*, p. 32.

The accumulative weight of the objections summarized above is so great that the writer unhesitatingly rejects the arch hypothesis as a possible explanation of the major structural features shown at Golden.[1] It is weak in its inherent fundamental assumptions, does not explain the many and peculiar coincidences in the facts observed along the line of the supposed unconformities, and is in several cases directly contradicted by dip and strike observations.

Proposed Explanation of the Structure at Golden: The geological conditions at Golden, outlined above, are best explained on the basis of extensive faulting practically parallel to the general strike of the formations. It is logical to believe that intense monoclinal folding of the "S" type shown to be characteristic of this part of the foothills could not be localized along a practically straight line without a decided tendency to form fractures and faults parallel to the general trend of the fold. On the accompanying geological sketch map of the vicinity of Golden the location of such faults is indicated by heavy lines, and it will be noted that these coincide with the lines of two of the unconformities of Eldridge in his arch hypothesis. The accompanying sections show in detail the faulting as postulated by the writer. In the case of section *A-A*, the double fault and its effect on the strata in the monoclinal fold is shown by a reconstruction of the latter in its original condition preceding each displacement (Figs. 4–7).

It will be noted that the faults are considered to have steep westward dips. The author has arrived at this conclusion from a study of the relationship of the course of the fault line to the topography, from a consideration of the character of the monoclinal fold, and the effect of the fault on the displaced rock formations. Ordinarily a thrust fault with dips as steep as indicated would be considered unusual, but we must carry in mind the fact that, in most cases of thrust faulting, lateral pressure is the dominant cause —as, for example, in the southern Appalachians. Here, therefore, thrust faults are as a rule characterized by flat dips. In the case of a monoclinal fold such as this, however, the maximum pressure

[1] Richardson, *U.S. Geol. Survey*, Folio 198, p. 11. It is of interest to note that both Lee and Richardson appear to doubt the truth of the arch hypothesis. In this connection see Lee, *op. cit.*, p. 32.

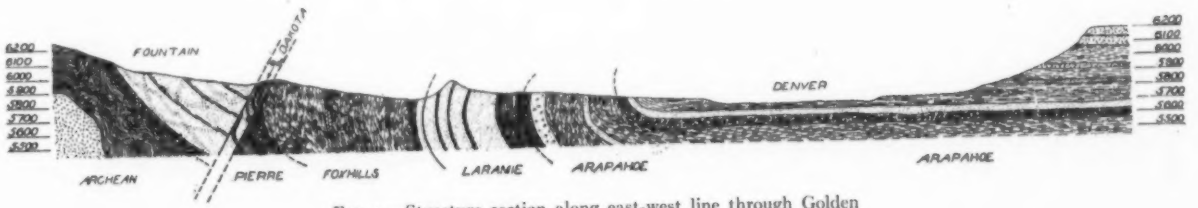

FIG. 4.—Structure section along east-west line through Golden

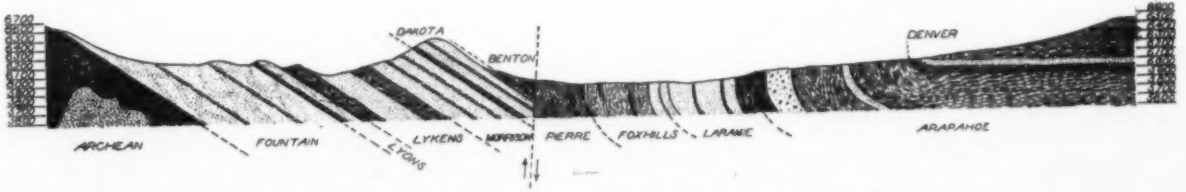

FIG. 5.—Structure section along east-west line, about four miles south of Golden

must have been nearly vertical and must have been manifest at the edges of the uplift in severely crowding the strata upon each other, owing to slipping and sliding on the steeply inclined Archean floor. Under these conditions the most logical planes of slipping would be the bedding planes, and the resulting faults would be strike faults with steep dips. The general dip and strike relationship shows normal easterly dips to be the rule in the older formations to the west of the fault plane, while the younger rocks to the east are characterized by overturned westerly dips. A consideration of the monoclinal fold will show that only a steep westward-dipping thrust fault as drawn by the writer can explain this relationship. Any eastward-dipping fault with overthrust from the east would bring younger horizontal rocks to rest upon

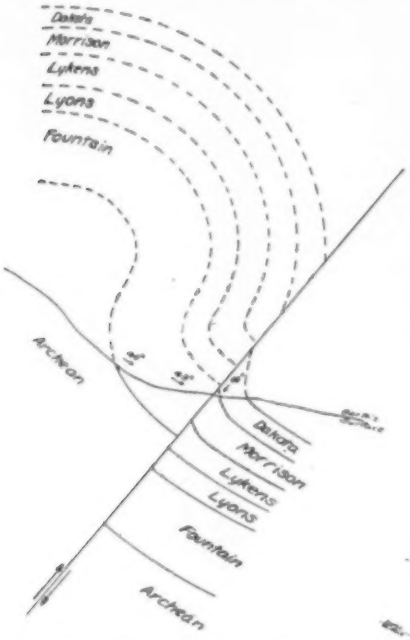

FIG. 6.—Detail of first fault shown on Fig. 4.

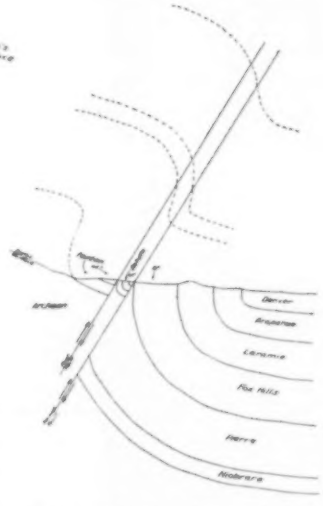

FIG. 7.—Detail of second fault (eastern one) shown on Fig. 4.

older steeply dipping ones, which is not the case. As will be seen from the sections, these faults are of the hinge type, with maximum displacements at Golden. This gradually decreases to zero toward the north and south.

All facts recorded by Eldridge and all facts observed by the writer accord perfectly with such an explanation. We should expect fault lines of this nature to be characterized by the crumpling and overturning of strata affected. The more sharply a formation is truncated the more evident the effects on its bedding planes should be. Maximum displacement and maximum disturbance should logically go hand in hand. The course of the fault plane and its position would determine whether a formation disappears from the bottom up or from the top down. As a general rule, with dips and strikes as observed, the formation on the west side of this fault plane should disappear from the top downward, while the formation on the east side should disappear from the bottom up. This is actually the case (Fig. 8).

Upon cursory examination the decided westward curve of the outcrops is somewhat surprising and seems to suggest that the eastern block represents the upthrow side. This is, however, not true, and the inward curve is the combined result of the gradual steepening and eventual overturning of the monoclinal fold as we approach Golden, and the displacement along the westward-dipping fault surface.

The actual inward sweep of the strata resulting from the writer's interpretation of the structure can readily be approximated as follows: The total thickness of strata actually cut out at Golden is about 10,000 feet. Therefore, the lowest bedding plane on the Fox Hills remaining at Golden must have been located at least 10,000 feet higher than its present position on the monocline before faulting. To this must be added the difference in elevation between the top of the Archean and the Fox Hills today (at least 1,200 feet) and a certain amount to allow for folding, hence 12,000 feet may be considered a safe estimate as to the minimum amount of throw necessary to bring the base of the Fox Hills from its original location in the monocline to its present position. A vertical drop of 12,000 feet on a fault plane dipping 55° westward will result in a

westward travel of 8,000 feet on the horizontal plane. The result of the displacement alone will be a decided westward heave in any

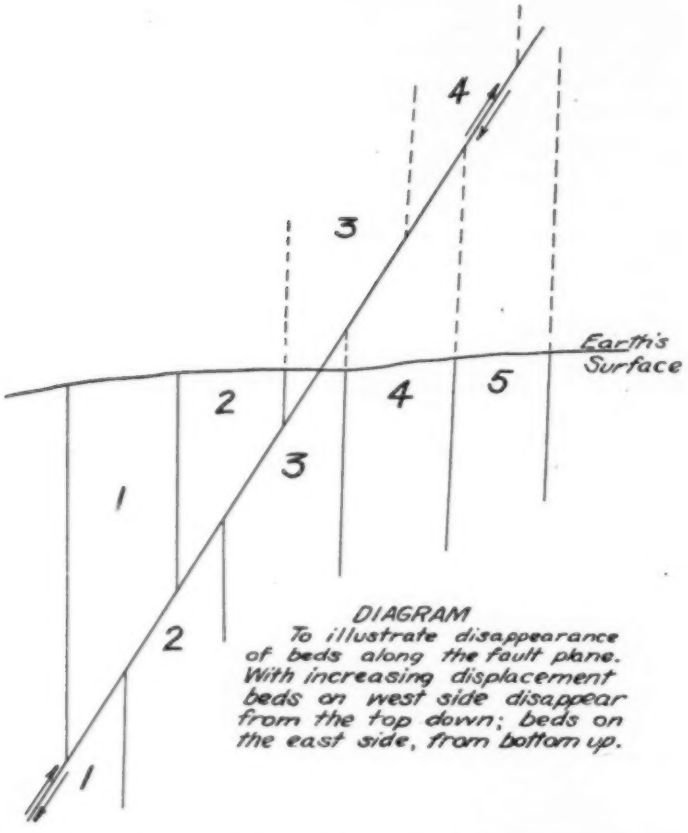

FIG. 8.—Diagram illustrating the disappearance of beds along the fault plane. Older beds (on left) disappear from top down; younger beds (on right) disappear from bottom up.

outcrop, and, since the amount of westward travel is dependent upon the amount of throw, each outcrop should show a progressively larger travel toward the west as we approach Golden.

This westward travel of 8,000 feet, due to the fault, will be augmented considerably by the change in the character of the monoclinal fold. As has been shown above, the monocline north and south of Golden is normal, gradually steeping and eventually overturning as it approaches Golden. The natural dip of the formations in the normal parts would, therefore, carry their outcrops far to the east of the steeper and overturned parts of the monocline, which, added to the effect of the faulting, is undoubtedly sufficient to account for the present situation of the various formations.

In connection with the writer's interpretation the following statement from Marvine[1] referring to the condition at Golden is of interest: "Some of the facts at hand indicate that a peculiar fault, depending on the nature of the sharp fold, and possibly connected with the lava near by, may have caused the present appearance."

The true nature of the fault was not realized by Marvine, for he also states "this may be caused . . . . by a fault which has pushed the higher portion of the series westward over the upturned edges of the lower portion, thus concealing much of the latter." Such a displacement is, however, incompatible with the data at hand and was hence rejected by later workers.

It is also of interest to note that Lee and Richardson[2] appear to doubt the existence of local unconformities in the foothill region. Dr. Patton also states in personal conversation that many of the phenomena observed by him in the foothills appear to be incompatible with the arch hypothesis.

The Boulder area.—The same structural peculiarities are shown at Boulder as at Golden, but not developed to the same remarkable degree and differing in some minor detail. Eldridge,[3] and subsequently Fenneman,[4] studied this area in detail and developed an explanation in every respect similar to that advanced for the conditions at Golden (Fig. 9). Elsewhere[5] the writer

[1] *Hayden Survey*, VII (1873), 137, 138.

[2] See Lee, *op. cit.*, p. 32; Richardson, *U.S. Geol. Survey*, Folio 198, p. 11.

[3] *U.S. Geol. Survey, Monographs*, XXVII, 105–14.

[4] *U.S. Geol. Survey Bulletin 265*, pp. 54–66.

[5] *Colo. School of Mines Quarterly*, April, 1917.

has discussed the Boulder area in detail and has shown that in this district also it fails to account for the local structural features and is fundamentally as unsound here as it is at Golden.

The accompanying sections show the writer's interpretation of the structure at Boulder. Here, as at Golden, steeply dipping strike faults have taken place parallel to the general trend of the foothills monocline, which are responsible for the disappearance of some formations and the notable decreases in thickness exhibited by others. The writer will not attempt to discuss these faults in

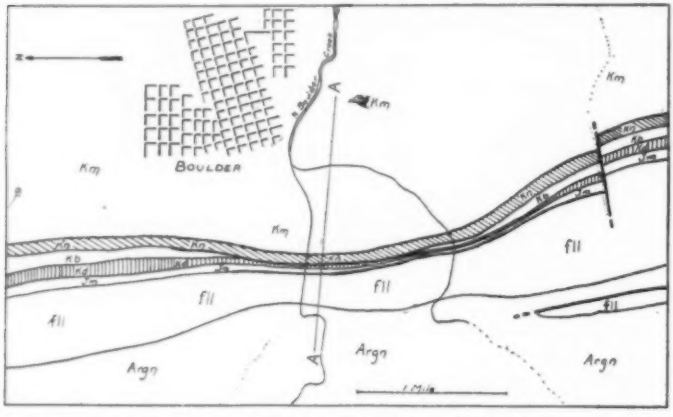

FIG. 9.—Sketch map of vicinity of Boulder (after Eldridge). Heavy lines indicate faults. For symbols, see Fig. 2.

detail. They resemble in every respect the faults at Golden and affect the strata in a similar way, but to a lesser extent. They are in absolute harmony with the manner of disappearance and thinning of the various formations, with observed dip and strike relationships, and do not postulate the extreme local subsidences and elevations required of the older explanation (Fig. 10).

Minor structural features.—Much minor faulting and folding, some of it of eccentric type, characterizes the great monoclinal uplift. Elsewhere[1] the writer has discussed this in some detail, especially for the purpose of bringing out the relation existing

[1] *Op. cit.*

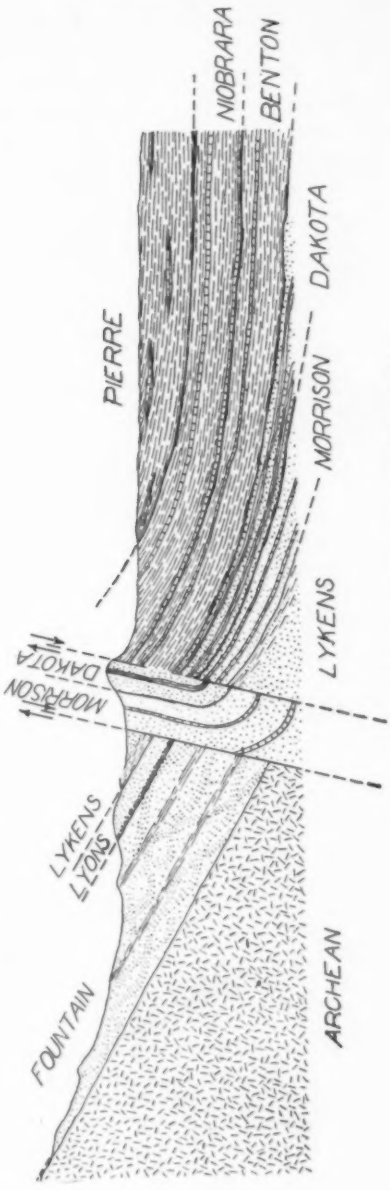

FIG. 10. East-west structure section through city of Boulder

between these minor structures and the huge thrust faults here described (Figs. 11–15).

Minor Folds: Two distinct types of minor folds can be recognized, *folds en échelon* and *drag folds*. The former pass practically invariably on their west flank into eastward-dipping faults with strikes nearly parallel to the axis of the fold. They represent

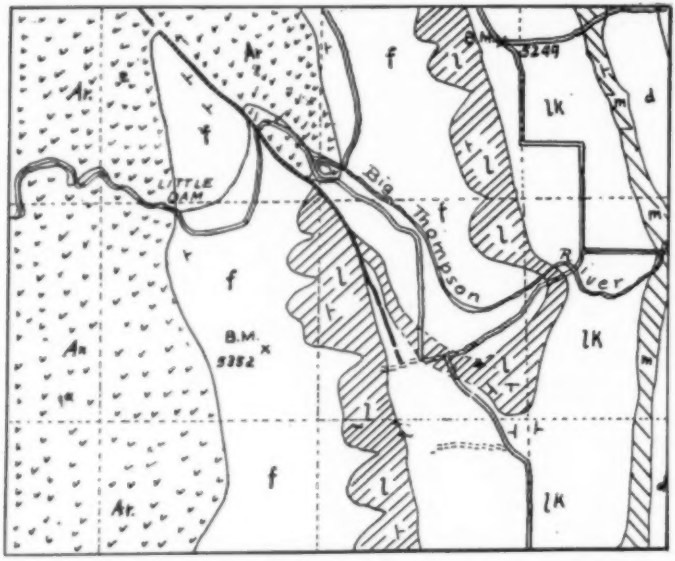

FIG. 11.—Geological sketch map of area on Estes Park road west of Loveland, showing characteristic fold *en échelon* and accompanying thrust fault. Section lines are indicated.

minor wrinkling, with overthrusts from the east subordinate in amount to the main monoclinal uplift and faulting. Other folds, noted especially in the shale series, represent adjustments by incompetent layers to stresses incident to the formation of the uplift.

Minor Faults: Both strike and dip faults are numerous, especially in the structurally disturbed areas at Golden and Boulder. They are all of slight displacement. They do not antedate the

uplift of the monoclinal fold, as stated by Eldridge, Fenneman, etc., but represent minor fracturing and slipping attendant upon, and consequent to, the formation of the main monoclinal uplift and its master-faults.

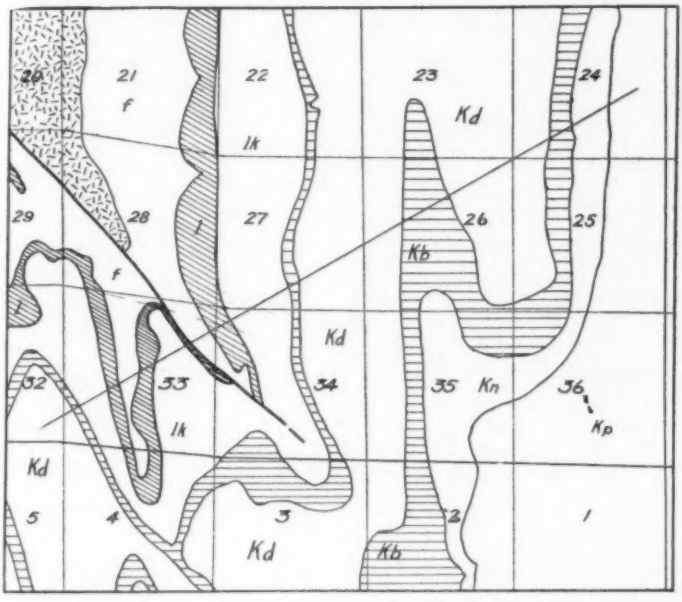

FIG. 12.—Geological sketch map of southwest corner of Loveland quadrangle, showing folds *en échelon*. For symbols, see Fig. 2.

SUMMARY

The master-monocline.—It has been shown by a reconstruction of the original foothills fold from observed dip and strike relationships that this represents an ideal monoclinal fold in strata originally continuous over the entire area of the Front Range, which gradually steepens and eventually overturns as it approaches Boulder and Golden. Contrary to former interpretations and general belief, the maximum overturn is above the earth's surface.

The main faults.—It has definitely been proved that the structural irregularities at Golden (and Boulder) cannot be explained

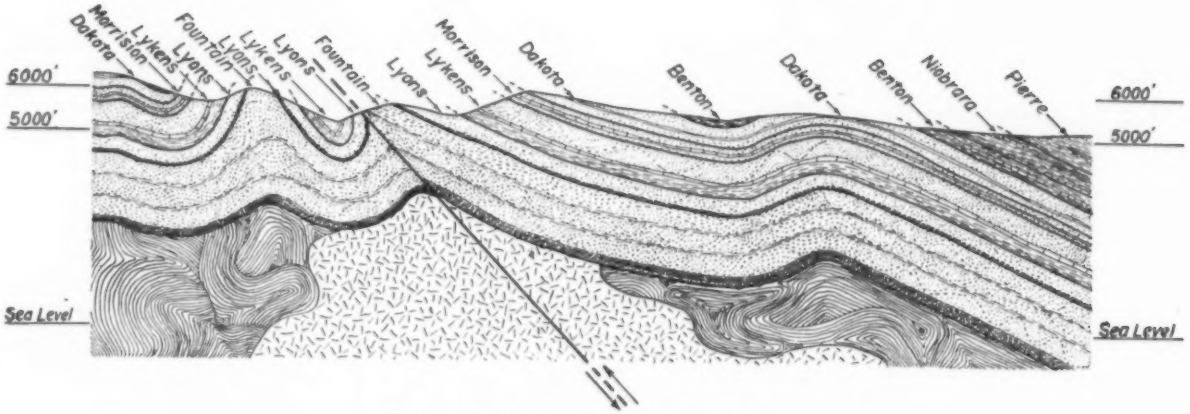

FIG. 13.—Section along line indicated on Fig. 12

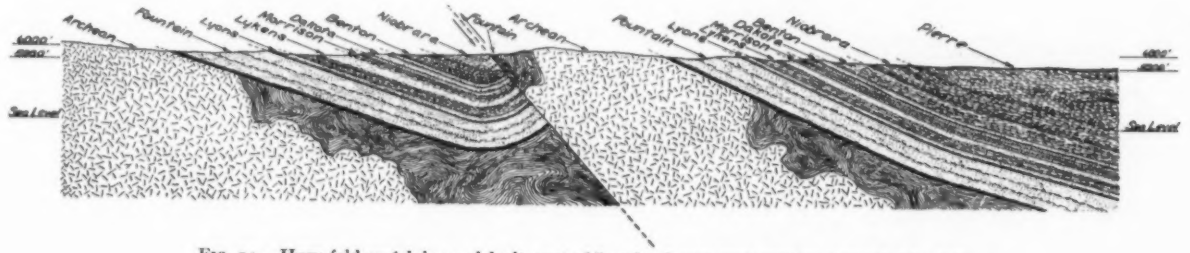

FIG. 14.—Huge fold *en échelon* and fault west of Loveland, east-west section, through Mt. Milner

as the result of repeated local arching and contemporaneous erosion, as attempted by former workers in this field. An alternative interpretation has been advanced by the writer which

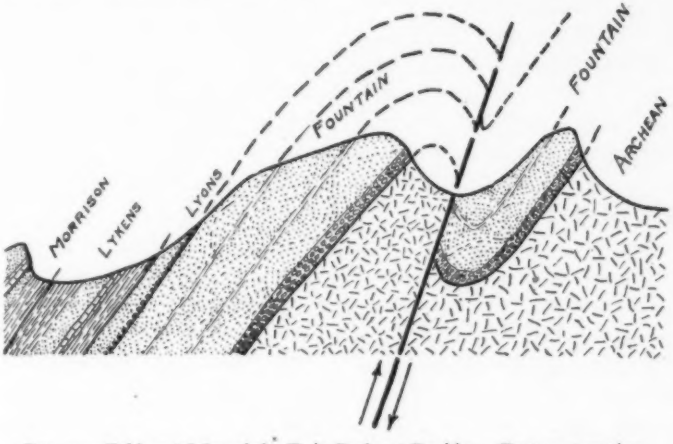

FIG. 15.—Fold *en échelon* of the Twin Peaks at Boulder. East-west section

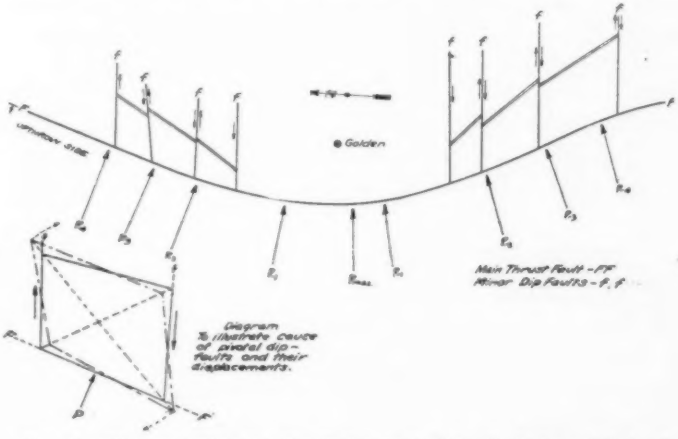
Golden
Main Thrust Fault - FF
Minor Dip Faults - f, f
Diagram to illustrate cause of several dip-faults and their displacements.

FIG. 16.—Diagram to illustrate the displacement of the dip faults and their relation to the large thrust faults at Golden. Small diagram shows distortion of interfault block due to pressure causing the main fault. The small arrows indicate the direction of displacement of interfault blocks.

postulates the presence of extensive strike faults with steep westerly dips and overthrust from the west. This interpretation is shown to be free from the inherent weaknesses of the older so-called arch hypothesis, and to be in perfect accord with all observed geological features.

Conclusion.—The formations represented in this area of the foothills range in age from Permo-Carboniferous to Paleocene. The Cretaceous formations certainly, the older probably, extended formerly over the entire area of the Front Range. At the close of Arapahoe time and during early Denver time the area to the west of the foothills rose, and the sedimentaries were folded into a normal monocline with average eastward inclination of about 45°. Locally (as at Golden and Boulder) excessive overturning occurred, accompanied by fracturing, and resulting in extensive overthrusts from the west along steeply dipping fault planes. Minor strike faulting, and dip faulting with hingelike displacements, as well as drag folding, accompanied and followed the major uplift and faults. The natural buckling and wrinkling of strata, where the pressure on the monoclinal fold was not intense enough to cause huge strike faults, resulted in the formation of folds *en échelon*, with their attendant overthrust faults from the east. The exact time of the uplift cannot be closely determined, except that the basal beds of the Denver are involved in the folding and that the composition of the upper beds of this formation shows that erosion had entirely cut through the sedimentary series over the site of the Front Range at the time of their deposition.

The sincere thanks of the writer must be expressed to Dr. H. B. Patton for advice and helpful suggestions in the preparation of this paper.

ON THE GEOLOGY OF THE ALKALI ROCKS IN THE TRANSVAAL

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Delft, Holland

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INTRODUCTION

In June 1910 I studied the geology of the occurrences of nepheline syenites in the Transvaal, and the results were published in the same year in a paper, "Oorsprong en Samenstelling der Transvaalsche Nepheliensyenieten," which contains a contribution to the geology and a petrographical description of the nepheline syenites and various allied rocks. In the following pages some geological questions will be treated more in detail and the main results of recent work of the Geological Survey of South Africa are added.

I am much indebted to Professor G. A. F. Molengraaff, of Delft, who placed his collection of rocks at my disposal, while the text has been much improved by his valuable suggestions; and also to Professor A. Lacroix, of Paris, the rock material being studied for the greater part in his laboratory.

For assistance during my stay in South Africa, my best thanks are due to the staff of the Geological Survey, particularly to Mr. A. L. Hall, who furnished some rock specimens from Rietfontein [451] and Spitskop [463].[1]

As a guide to the stratigraphy and the geological dates mentioned below, a table of the Transvaal formations is entered (see Table I).

IGNEOUS COMPLEX OF THE BUSHVELD

The nepheline syenites of the Transvaal make part of a complex of igneous rocks, which is intrusive as a laccolith or laccolithic sheet between the upper strata of the Transvaal system and the strata of the unconformably overlying Waterberg system.

The laccolithic character of this complex was recognized by Molengraaff,[2] who grouped them under the name "plutonic series of the Bushveld";[3] it includes igneous rocks, which have a high soda content as a common character. The name used by other authors, "igneous complex of the Bushveld" or "Bushveld igneous complex," has the same signification and can be considered as the official one, because the Geological Survey of the Transvaal has adopted it.

PLACE OF THE MAIN TRANSVAAL LACCOLITH

The western boundary of the part of the complex in the Central Transvaal, which has been uncovered by erosion, is found nearly 15 km. to the west of the Marico River; the eastern one, nearly 25 km. to the west of Lydenburg; the medium breadth is nearly 100 km.

But probably it covers a much larger area; at least it appears again between the Magalakwin River and the sources of the

[1] Throughout this paper numbers in brackets refer to official designations for farms in South Africa.

[2] G. A. F. Molengraaff, "Géologie de la République Süd-Africaine du Transvaal," *Bull. de la Soc. Géol. de France*, Série 4, T. I, 1901, p. 13.

[3] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 42.

Matlabas and to the north of the Palala Plateau, where it extends to the north to near the Limpopo, nearly 30 km. to the south of the northern boundary of the Transvaal.[1]

BOTTOM OF THE LACCOLITH

The bottom of the laccolith is formed everywhere by the upper strata of the Pretoria series, generally consisting of Magaliesberg quartzite.

Therefore the rocks of the laccolith in the Central Transvaal are for the greater part surrounded by the upper Pretoria strata; in the strata of the Transvaal system, which dip everywhere toward the central part of the complex, the dip of the strata decreases when the distance from the complex increases. Because the Magaliesberg quartzites of the Pretoria series have specially resisted erosion we now see them as a ridge surrounding the complex.

We see that the bottom of the laccolith is determined, but the the place of the roof of the laccolith is uncertain.

ROOF OF THE LACCOLITH

The part of the laccolith, which has not been uncovered by denudation, is covered by the strata of the Waterberg system and partly by the younger strata of the Karroo-system. Between the basal conglomerate of the sandstone series of the Waterberg system and the underlying rocks of the Bushveld complex we sometimes find a series of felsitic rocks, which other authors have considered as being directly connected with the deep-seated rocks of the laccolith, but which the Geological Survey of the Transvaal regards as a lower division of the Waterberg system.

The Waterberg system then includes:

Waterberg system	Upper Division	Sandstones, grits, and conglomerates
	Lower Division (Volcanic series)	Felsites and allied volcanic rocks with interbedded shales

[1] G. A. F. Molengraaff, "Geologische Aufnahme der Süd-Afrikanischen Republik," *Jahresbericht über das Jahr 1898*, Pretoria, 1900; G. G. Holmes, "Some Notes on the Geology of the Northern Transvaal," *Trans. Geol. Soc. South Africa*, VII (1904), 51–56.

The roof of the laccolith would, then, not be formed by the sandstone series of the Waterberg system but by the volcanic

TABLE I

TABLE OF THE GEOLOGICAL FORMATIONS OF THE TRANSVAAL[1]

Main Igneous Intrusions	Sedimentary Rocks			Age
		Superficial Deposits		
		Unconformity		
	Karroo system	Upper Karroo	Bushveld amygdaloid	?
			Bushveld or Buiskop sandstone	?
		Middle Karroo	Highveld or Beaufort series with coal measures	Permo-Carboniferous
		Lower Karro	Ecca shale series	Permo-Carboniferous
			Dwyka conglomerate or tillite	Permo-Carboniferous
Bushveld igneous complex intruded as an unconformational laccolithic sheet between the strata of the Pretoria series and those of the Waterberg system		*Waterberg system*		
		Unconformity		
	Transvaal system	Pretoria series		Probably pre-Devonian
		Dolomite series		Probably pre-Devonian
		Black Reef series		Probably pre-Devonian
		Unconformity		
		Ventersdorp or Vaal River system		?
Old grey granite.—The exact age of the intrusion or the intrusions of this granite is not yet known. The intrusion, however, took place certainly after the deposition of the rocks of the Swaziland system and before the deposition of the rocks of the Transvaal system		Unconformity		
	Witwatersrand system	Upper division, containing the famous auriferous Main Reef series		?
		Lower division		?
		Unconformity		
		Swaziland system		?

series, in which sometimes red granites can be seen clearly intrusive. But the question of the mutual relation between the rocks of the

[1] Cf. G. A. F. Molengraaff, "The Deposits of Iron Ore in the Transvaal," in *The Iron Resources of the World* (Stockholm, 1910), p. 1060.

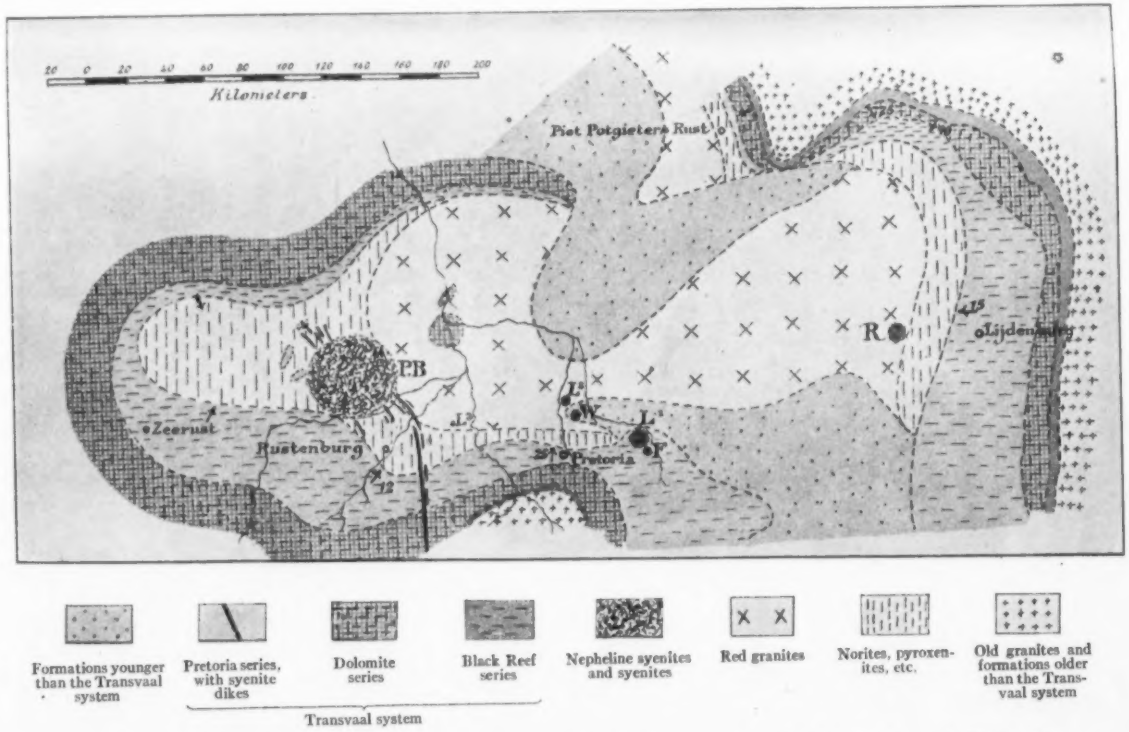

FIG. 1.—Geological sketch map of the Central Transvaal with the occurrences of nepheline syenites and allied rocks*

*Complex of the Pilandsberg: L^1, Leeuwfontein [320]; L^2, Leeuwkraal [396]; L^3, Losperfontein [119]; *F*, Franspoort [426]; *W*, Walmansdal [116]; *R*, Rietfontein [451

Bushveld complex, the volcanic series, and the sandstone series, of which the contradictory facts already were enumerated by Molengraaff,[1] has not been solved in this way.

As far as concerns this mutual relation, the following facts can be considered as certain:

1. The deep-seated rocks are intrusive in the volcanic series.
2. Dikes which are genetically connected with the deep-seated rocks (felsophyres with the red granites, tinguaites with the nepheline syenites) cut through the sandstone series.
3. The volcanic series show the characteristics of effusive rocks and include sediments (shales and sandstones) in the higher horizons.
4. Sometimes more, sometimes less, clearly the sandstone series rest unconformably upon the volcanic series, the transition being characterized by the existence of conglomerates.
5. In the basal conglomerate of the sandstone series felsitic pebbles sometimes occur.
6. Fragments of a conglomerate, which very closely resembles the basal one, are found in the phonolites of the Pienaars River valley.

When we try to make these facts agree with each other, we meet with great difficulties. It seems to be certain that an effusive period has preceded the main intrusion and that both are connected genetically.

But when we admit, for instance, that the sandstone series are older than the effusive and intrusive series, then the occurrence of felsitic pebbles in the basal conglomerate and the more or less distinct unconformity with regard to the felsites, and also the effusive character of the latter ones and their alternation with sediments, are inexplicable. When we admit that the sandstone series are younger than the effusive and intrusive period, then the intersecting dikes, which are the equivalents of the deep-seated rocks, and also the intrusions of red granite in the sandstone series are unexplained.

We could explain the facts in a rather satisfactory way if we admitted effusion and several intrusions from a deeper-seated

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 59.

mother-magma and considered the Waterberg sandstone as younger than the effusive, but older than the main intrusive, period; then, however, there is no genetic connection between effusion and intrusion.

With H. Kynaston and E. T. Mellor,[1] we can admit a prolonged activity of the Bushveld magma, while the sandstone series were deposited between the main intrusive and effusive period and the later intrusions.

That the nepheline syenites are younger than both the norites and the granites will be proved in the following pages. Only detailed geological and petrographical investigations can clear the true succession from the remnants left after the advanced denudation.

In any case, the following reasons make it undesirable to unite the volcanic series and the sandstone in the Waterberg system.

Over large surfaces at the base of the sandstone series we find developed a basal conglomerate, which rests unconformably, not only upon the felsites, but also upon the red granites; and in the Zoutpansbergen we also find them resting upon much older formations, such as the old granites. Thus it forms a geological horizon over the whole of Central Transvaal and marks an extensive unconformity.

As a rule the pebbles of felsites are rare in this conglomerate, although the relative quantity may increase locally and the unconformity be locally less well developed. In the Waterberg district[2] the conglomerate is principally composed of pebbles of jasper, quartzite with magnetite, white quartzite, schistose quartzite with muscovite, quartz, chert, and felsophyre, which, except the felsophyre, belong to the Swaziland system (Barberton series). Consequently this unconformity must be maintained as a horizon of separation, and the volcanic series must be separated from the sandstone series of the Waterberg system and can either be included in the igneous complex of the Bushveld or else considered as a

[1] H. Kynaston and E. T. Mellor, *The Geology of the Waterberg Tin Fields. Memoir No. 4, Geological Survey of the Transvaal*, Pretoria, 1909.

[2] G. A. F. Molengraaff, "Geologische Aufnahme der Süd-Afrikanischen Republik," *Jahresbericht über das Jahr 1898*, Pretoria, 1900.

separate volcanic series, which is younger than the Transvaal system and older than the Waterberg system and the main laccolithic intrusion.

ACCOMPANYING DIKES AND INTRUSIVE SHEETS

Except the basic rocks, which alternate with the shales and quartzites of the Pretoria series and which are perhaps genetically connected with the intrusion, numerous syenite dikes cut through the Pretoria series and the Dolomite series, and intrusive sheets of red and grey syenite are found in the dolomites. The well-known dike of porphyritic nepheline syenite of the station Wonderfontein in the Potchefstroom district can be followed over Breedts Nek in the Magaliesbergen as far as the nepheline syenites of the Pilandsberg.

At the contact of the intrusive sheets, which have a thickness of three to forty meters, the syenite is finer-grained to microcrystalline, and the dark dolomite has been changed into white marble.

TECTONIC CHANGES CONNECTED WITH THE INTRUSION

The study of the Transvaal system in the neighborhood of the laccolith proves that there are numerous dislocations directly connected with the intrusion.[1]

The strata sank under the weight of the intrusive mass; this explains the increasing of the dip, when the distance from the complex decreases, and also explains why the complex is surrounded by a ridge of harder sediments, which dip toward the central part. In the neighborhood of Pretoria and from there to the west, as far as Rustenburg, we see the ridge of the Magaliesberg quartzites uninterrupted, the strata dipping toward the intrusive complex.

To the east of Pretoria is a series of step faults, which can be followed easily in parallel ridges, which consist of quartzites of the Pretoria series.

We see the dislocations in a remarkable manner where the periphery of the complex forms a re-entering angle as, for instance, at Franspoort east of Pretoria. The ridge of the Magaliesberg

[1] This question was discussed in detail by Molengraaff; cf. *Geology of the Transvaal* (Johannesburg, 1904), p. 50.

quartzites and the accompanying Daspoort and Timeball quartzites here suddenly bend to the southeast. The dip of the strata continues toward the red granites, but the outer ridge of the Magaliesberg quartzites has been fractured and extended in length; the ridge is broken by "poorten." The inner ridges (Daspoort and Timeball Hill quartzites) were strongly pressed in a direction slightly oblique to the strike of the strata. All this is clearly shown by the grouping of the quartzite hills in the neighborhood of Pretoria. That the intrusion and dislocations are directly connected is also evident from the study of the zones of contact in the surrounding sediments in disturbed and undisturbed regions.

CONTACT METAMORPHISM

The quartzites, clay-slates, and "greywackes" of the Transvaal system are strongly metamorphosed by the intrusion of the laccolith. The contact phenomena in connection with the laccolith were first mentioned by Molengraaff and later studied in detail by Hall.[1] The quartzites of the Magaliesberg Range are recrystallized and consist of more or less hexagonal quartz crystals, which sometimes attain a diameter of more than one centimeter; in the clay slates cordierite, andalusite, and biotite appear. The metamorphism decreases when the distance to the laccolith increases, but even the rocks of the dolomite series are metamorphosed. Where the Transvaal system is much disturbed and has undoubtedly been exposed to high pressure, the metamorphosed rocks show a different character in their structure, as well as in their mineralogical composition. These rocks are connected by transitions with the pure contact-rocks of the undisturbed regions.

Muscovite, glaucophane, and zoisite, which are characteristic for the dynamometamorphic crystalline schists, and in small quantities the contact minerals, cordierite, andalusite, and tourmaline, occur in the metamorphosed rocks. Hall decides upon the contemporaneous action of contact and dynamometamorphism in the disturbed regions, from which it is once more evident that the intrusion was directly connected with the dislocations.

[1] A. L. Hall, "Über die Kontaktmetamorphose an dem Transvaalsystem im östlichen und zentralen Transvaal," *Tschermaks Min. u. Petr. Mitt.*, Bd. XXVIII, Heft 1–2 (1909), pp. 115–52.

ROCK TYPES OF THE BUSHVELD COMPLEX

1. *Red granites.*—The acid rocks of the laccolith are amphibole-biotite granites, which are very poor in dark constituents. Principally they show typical granophyric structure. They differ petrographically from the old granites, in essential features enumerated by Molengraaff.[1] In the red granites muscovite is entirely wanting.

2. *Norites, gabbros, and pyroxenites (with segregations of iron ore).*—Nearly everywhere at the periphery of the red granites we find a zone of basic and ultra-basic rocks. The basic rocks are found near the western and southern part of the Pilandsberg; they accompany the Magaliesberg quartzites in a south-southeasterly direction to the environs of Rustenburg, where they bend to the east in the direction of Pretoria. The Zwartkoppies and Pyramids have been given their respective names from the color and the form of the small hills, which are composed of these rocks. Finally, they are found from the environs of Belfast to those of Piet Potgietersrust; still farther to the north they are in contact with the old granites. Iron ore has been segregated from these basic rocks at several places; lenticular masses of magnetite are developed nearly everywhere around the Bushveld. At some places these masses are thicker than one hundred meters. The iron ore is magnetite, sometimes with chromite. In the norites the percentage of magnetite goes on increasing, as one approaches the pure magnetite. Ultra-basic pyroxenites and peridotites fill the shallow basin to the West of the Pilandsberg, bounded on the south by the Schurveberg and the Zeerust Hills, on the west by the Marico Hills, and on the north by the Dwarsberg.

3. *Nepheline syenites and syenites.*—These rocks, of which the mode of occurrence and the composition are more fully described in the following pages, are uncovered at several places, often near the boundary of norites and granites.

PNEUMATOLYSIS

As a result of the cooling down and contraction of the intrusive complex and the pressure upon the surrounding strata, numerous

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 44.

fissures were formed, in which different minerals crystallized from the circulating emanations of the magma. The numerous occurrences of tin ore are genetically connected with the red granites of the Bushveld. The copper and silver ores of the Albert mine and the cobalt ores of Balmoral are found in red granite. Finally, we find numerous ore deposits in the Pretoria series, the origin of which is probably directly connected with the intrusion of the Bushveld complex.[1]

THE OCCURRENCES OF ALKALI ROCKS

Common to the occurrences of alkali rocks is the abundance of nepheline syenites. They are exposed at the following places:

1. In the Pilandsberg (Rustenburg district), where they are accompanied by syenites, effusive rocks, and dike rocks.

2. At the boundary of the farms Leeuwfontein [320] and Zeekoegat [287], northeast of Pretoria, where they are accompanied by syenites, leeuwfonteinites, effusive rocks, and dike rocks.

3. On the farms Rietfontein [451] and Spitskop [463], west of Lijdenburg.

4. On the farm Franspoort [426], south of Leeuwfontein [320] (Pretoria district).

5. On the farm Walmansdal [116], northwest of Leeuwfontein [320].

6. On the farm Leeuwkraal [396], still farther to the northwest.

7. On the farm Losperfontein [119] (Rustenburg district).

8. Numerous dikes can be followed from the Pilandsberg in a northwesterly and a southerly to southeasterly direction.

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (1904), p. 52; A. L. Hall, "Geological Notes on the Bushveld Tin Fields, etc.," *Trans. Geol. Soc. South Africa*, VII (1905), 47–55; F. H. Hatch and G. S. Corstorphine, *Geology of South Africa* (London, 1909), p. 216; E. T. Mellor, "Field Relations of the Transvaal Cobalt Lodes," *Trans. Geol. Soc. South Africa*, X (1907), 36; H. Kynaston, "Anniversary Address of the President of the Geological Society of South Africa for 1908," *Trans. Geol. Soc. South Africa*, XII (1909); H. Recknagel, "On Some Mineral Deposits in the Rooiberg District," *Trans. Geol. Soc. South Africa*, XI (1908), 83; "On the Origin of the South-African Tin Deposits," *Trans. Geol. Soc. South Africa*, XII (1909), 168; H. Merensky, "The Rocks Belonging to the Area of the Bushveld Granite Complex in Which Tin May Be Expected, etc.," *Trans. Geol. Soc. South Africa*, XI (1908), 25; H. Kynaston and E. T. Mellor, "The Geology of the Waterberg Tin Fields," *Memoir No. 4, Geological Survey of the Transvaal*, Pretoria, 1909.

THE PILANDSBERG

Where the ridge of the Magaliesberg quartzites—the direction of which was southeast and northwest, to the north of Rustenburg—bends again to the west, a mountain group arises from the rolling

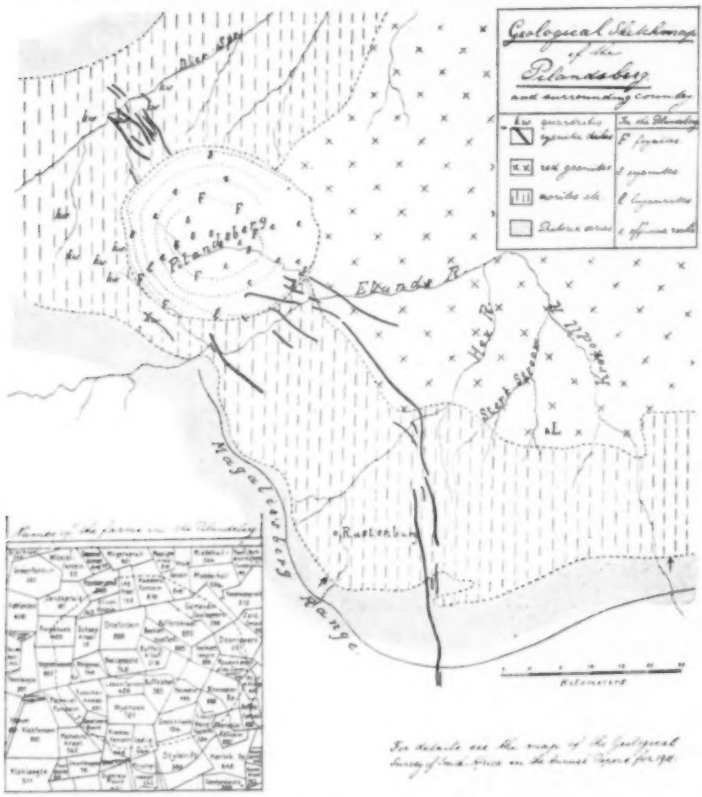

FIG. 2.—Geological sketch map of the Pilandsberg

and undulating country of norites and granites. It has an almost circular outline with a diameter of 15 miles from north to south and 18 miles from east to west. Long ridges and isolated mountains are separated by broad valleys, in which small rivers, dried up in winter, have cut deep valleys with vertical walls.

The first explorer who mentioned the composition of the Pilandsberg and the surrounding region was Adolf Hübner, in his description of a voyage from Potchefstroom to Inyati.[1] Evidently he had observed the peculiar character of these rocks, because he writes: "Am meisten Beachtung verdient wohl das unten zu beschreibende Gestein der Pilandsberge, welches entschieden als ein basisches plutonisches Gestein zu den Grünsteinen gerechnet werden muss." He crossed the Magaliesberg Range along the Hex River at Olifants Nek and traveled from there to Morgenzon [427] (the same direction which the road from Rustenburg to the Pilandsberg still follows); as the rock of the plain of Rustenburg he mentions a typical medium-grained greenstone, which near the contact with the rocks of the Magaliesberg Range crops out in thick sheets.[2] Then he crossed the Elands River and reached the Pilandsberg, which, he says, consists of mountains of greenstones from about 400 to 600 feet high. The meaning of his sentence, "Die Gesammtheit der Quarze bildet ein wahres Massengebirge," is not very clear. He mentions that a part of the mountains consists of a rock which seems to be a "hornblende porphyry," but which shows a syenitic character on closer examination. Because it consists of two minerals, a red "felsite" and a black amphibole, Hübner says that it is not a normal porphyry, though the red feldspar (orthoclase) predominates. The amphibole does not form crystals, but shows rather regular forms. As an interesting feature of this perhaps quite new rock, he mentions the numerous inclusions of clay slate and granite, which do not show any contact metamorphism. According to Hübner, this rock would cover a large area in the Pilandsberg. At several places, e.g., behind the negro town on Saulspoort [369] in the northeastern part of the mountains, granites and eruptive breccias, which contain fragments of porphyrite and granite, occur. Because Hübner mentions that he visited the missionary station on Saulspoort, he perhaps speaks about these rocks, which occur in the neighborhood of syenites with red feldspars.

[1] Adolf Hübner, "Geognostische Reisen in Süd-Africa," *Peterm. Geogr. Mitt.*, XVIII (1872), 424, 426.

[2] These rocks probably are the norites with schistose structure in the margin of the igneous complex of the Bushveld.

Nearly at the same time as Hübner, Carl Mauch[1] made geognostical studies in the central part of South Africa. In a chapter, "Mein erstes Jahr in der Transvaal Republik," he describes his "Irrfahrten in den Pilaans-Bergen." Coming from Rustenburg, he passed a conical hill and entered the central part of the mountain complex and found "quartz porphyries" with a violet-brown groundmass in the bed of a rivulet. After nearly perishing with hunger and thirst, he was received hospitably in the house of the missionary, who still lives in the native *stadt* on Saulspoort. From the western part of the mountains he mentions pieces of copper ore, magnetite, fluorine, and pebbles of gneiss. Most probably his quartz porphyries are the rocks without quartz, with porphyritic feldspars in a reddish, dense or fine-grained groundmass, which are the effusive equivalents of the syenites and nepheline syenites of this region. His gneiss probably is the schistose lujaurite which covers large areas in the western and southern part of the mountains.

In his sketch of the South-African Republic, G. A. F. Molengraaff[2] gives a review of the knowledge about the rocks of the Bushveld, and here the results of Mauch and Hübner are mentioned.

In 1898 J. A. L. Henderson[3] described a syenitic rock from the Pilandsberg as pilandite. The true character of the rocks of the Pilandsberg was recognized by Molengraaff[4] in 1904. In a short geological description of the Pilandsberg and a part of the Rustenburg district he mentions that different varieties of foyaites are of widespread occurrence and the schistose varieties, which are very rich in aegerine, are compared with the lujaurites of Greenland. The rock specimens, which Molengraaff collected, were studied by me, and the results of this study were published in the petro-

[1] Carl Mauch's "Reisen im Innern von Süd-Afrika, 1865–1872," Ergänzungs-Bd. VIII (1873–74), *Peterm. Geogr. Mitt. No. 37*.

[2] G. A. F. Molengraaff, "Schets van de Bodemgesteldheid van de Zuid-Afrikaansche Republiek," *Tijdschr. Kon. Aardr. Gen.* (Leiden, 1890), p. 604.

[3] J. A. L. Henderson, *On Certain Transvaal Norites, Gabbros, Pyroxenites and Other South-African Rocks*. London, 1898. Dulau and Co.

[4] G. A. F. Molengraaff, "Preliminary Note on the Geology of the Pilandsberg and a Portion of the Rustenburg District," *Trans. Geol. Soc. South Africa*, VIII (1905), 108.

graphical part of my first paper. In the winter of 1910 I visited the occurrences of nepheline syenite in the Transvaal, especially that of the Pilandsberg (during the last two weeks of June).

After this visit I was able to give a brief description of the general geology of the neighborhood.[1] I showed that these mountains consist of red syenites, nepheline syenites, and their porphyritic and dense equivalents, and, with a sketch map, that the main rock types are disposed in concentric circles. As far as concerns the red syenites, I was able to show that they often are covered by the effusive rocks, while they probably were older than the nepheline syenites of the complex. There was clear evidence that the rocks of the Pilandsberg intrusion are younger than the granites and norites of the igneous complex of the Bushveld; dikes, which are genetically connected with the intrusion, cut through the granites and norites. The intrusion of nepheline syenites on Leeuwfontein [320] was shown to be certainly younger than the Waterberg system, because a dike of tinguaite, which has the same chemical composition as the normal foyaites of Leeuwfontein, cuts through Waterberg sandstones and conglomerates on Paardefontein [338].

The mapping of the Pilandsberg and surrounding area was carried out in the next year by Dr. Humphrey, in company with Dr. P. Wagner, in connection with the work of the Geological Survey of South Africa.[2] Humphrey divides the whole of the rocks into two main groups: the nepheline syenites and phonolites; and the alkali syenites and trachytes. Each of these groups contains a plutonic and an effusive representative and "the reason for this classification is that the rocks forming the Pilandsberg are the denuded remnants of what was once a stupendous volcano, comparable in size with the greatest of the present-day active volcanoes."

General character of rocks.—The foyaites and other allied rocks in Professor Molengraaff's collection have been described by me

[1] H. A. Brouwer, *Oorsprong en samenstelling der Transvaalsche Nepheliensyenieten* (1910), pp. 12–29.

[2] W. A. Humphrey, "The Volcanic Rocks of the Pilandsberg," *Trans. Geol. Soc. of South Africa*, August 19, 1912; "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 77.

in detail. Because the study of the alkali syenites and effusive rocks which were collected during my visit in 1910 has been postponed by my departure for the East Indies, we will mention the most characteristic features of the latter rocks, as they have been briefly described by Humphrey.

The richness in pneumatolytic and thermal minerals (especially fluorspar) is characteristic for the rocks of the whole region; accordingly the loss on ignition is always considerable.

Besides the coarse- to medium-grained intrusive rocks and the effusive ones, transitional types have a great development. A series of porphyrites which graduate through all the types between true lavas, intrusive sheets, and dikes often form an unbroken series paralleling the effusive rocks.

Nepheline syenites: The nepheline syenites partly belong to the group of the foyaites and are usually coarse-grained. They are connected by transitions with the lujaurites, which are characterized by the abundance of small needle-shaped crystals of aegirine and are quite similar to the lujaurites of Greenland and the peninsula of Kola. The latter rocks principally are found in the southern part of the mountains, while lujauritic rocks only exceptionally occur in the central part. The foyaites have been frequently found by Humphrey in dikes, traversing the various effusive rocks and the red syenites.

If we divide the foyaites according to the character of the dark minerals, we find that nearly all the subgroups are represented and, in the porphyritic varieties, we also find aegirine, alkaline amphiboles, and biotite, either characterizing different rock types or occurring together in the same rock. The amphiboles are rich in alkalies and often show peculiar properties which are similar to those often mentioned in the literature of the foyaitic and theralitic rocks. Their optical and chemical properties have not yet been studied in detail, but they are known to have the properties of the barkevikitic, kataforitic, or arfvedsonitic amphiboles.

The isolated range of hills to the southeast of the Pilandsberg proper, which bends around with the lujaurites, consists of aegirine-amphibole foyaites, in which the amphibole has a pronounced zonal structure. The differences in color are progressive from brown

in the central part to green in the margin, while a turning of the plane of optic axes from parallel to the plane of symmetry in the central part to normal to it in the margin was often observed. The extinction angles in sections parallel to [010] are up to 40°. Amphiboles in which the plane of optic axes is normal to the plane of symmetry have also been found in pegmatitic segregations in aegirine-amphibole foyaites on Buffelspan [585]. Their angle of optic axes is very small and the extinction angle **b**:*c* is about 14°. In rocks from Wijdhoek [701] many properties of the amphiboles agree with those of the green amphiboles which Ussing[1] described in rocks from Greenland.

Coarse-grained foyaites are largely developed in the central, and also in the northern, part of the mountains. The hills and a part of the valley on and near Boekenhoutfontein [889] consist of foyaites, which contain aegirine and sometimes are very rich in biotite; more to the south, at Buffelspan [585], coarse-grained aegirine-amphibole foyaites are found. Rocks with the same structure occur in the western part of Houwater [496] and gray foyaites cover a large surface on Schaapkraal [12]. Leucocratic foyaites with aegirine as the only dark constituent are found in the western part of Wijdhoek [701], near the eastern boundary of Tusschenkomst [331]; they are associated with aegirine-amphibole foyaites. They form a complex of isolated small hills in a valley, surrounded by ridges of effusive rocks. The foyaites can be followed to the southern part of Leeuwfontein [429] and to Welgeval [749]. At Wijdhoek [701] they show a considerable amount of variation in structure and composition; we find gray feldspar rocks, which contain biotite as the only dark constituent, varieties which are rich in nepheline, and porphyritic equivalents in which the dark minerals appear as phenocrysts enclosing the elements of the fine-grained groundmass.

The lujaurites are characterized by their richness in fine needles of aegirine. In a forthcoming petrographical paper this group will be described in detail. Aegirine always predominates; arfved-

[1] N. V. Ussing, "Mineralogisk-petrografiske Undersögelser of Grönlandske Nefelinsyeniter og beslaegtede Bjaergarter," *Meddelelser om Grönland*, XIV (1894), 210.

sonite is a rare constituent of the rocks from the Pilandsberg, while true arfvedsonite lujaurites have been described by Ussing from Greenland. The lujaurites are connected with the foyaites by rock types poorer in dark minerals, aegirine with the needle form gradually disappearing. Like the lujaurites from other regions (Greenland, Kola peninsula, and Los islands), the rocks of the Transvaal are characterized by an abundance of rare minerals. For example, the new mineral molengraaffite,[1] of the eucolite group, which sometimes occurs in the foyaites, is very common in these lujaurites.

At both sides of the Rustenburg road, on Ledig [744], we find tinguaitic rocks and porphyritic lujaurites between the high lujaurite hills and the norites; to the east the lujaurites can be followed to Doornhoek [134]. Their southern parts are covered by effusive rocks. To the northwest, bending round with the periphery of the Pilandsberg, we can follow the lujaurites to the southwestern part of Wijdhoek [701]; farther to the northwest the periphery of the complex is formed by red to light-red syenitic rocks. On Tusschenkomst [331] we find the same lujaurites in contact with the effusive rocks, where a valley separates ridges of the two rocks.

The tops of the eroded lujaurite ridges are similar to those of inclined crystalline schists.

We find the lujaurites and their porphyritic equivalents also in the western, northern, and northeastern part of the complex, beside the red syenites; in the eastern part, where the effusive rocks have their greatest development, the latter rocks cover the whole surface from the periphery to the central foyaites. Probably the lujaurites occur there at greater depth. The nepheline syenites and the allied rocks which hitherto have been studied microscopically belong to the following groups:

1. Aegirine foyaites
   Leucocratic rocks
   Mesocratic rocks
   Foyaitic lujaurites

[1] H. A. Brouwer, "Molengraaffit, ein neues Mineral in Lujauriten aus Transvaal," *Centralbl. f. Min., etc.*, 1911, p. 129.

2. Lujaurites
   a) Eucolite-molengraaffite lujaurites
   b) Eucolite lujaurites
   c) Eucolite-astrophyllite lujaurites
   d) Aenigmatite lujaurites
   e) Lujaurites without eucolite
3. Aegirine-amphibole foyaites
4. Aegirine-biotite foyaites
5. Lujaurite porphyries
6. Aegirine-nepheline syenite porphyries without foyaitic structure
7. Aegirine-amphibole-biotite-nepheline syenite porphyries
8. Tinguaite porphyries

Syenites: The syenites generally have a red or reddish color; they principally consist of feldspar, while the dark-colored minerals have usually been altered into chlorite. Iron ores, titanite, apatite, and fluorspar are further constituents of these rocks.

Humphrey[1] mentions that the red syenites of the eastern, western, and central parts of the Pilandsberg have various points of dissimilarity in the hand specimens; those of the east, on Rhenosterspruit, being almost entirely composed of feldspar, while the other localities furnish rocks in which is much iron ore. The latter rocks are very decomposed. The feldspars are microcline, orthoclase, and anorthoclase. Two analyses of red syenites, which have been published in the *Annual Report of the Geological Survey of South Africa* for 1911, show that there are considerable differences in chemical composition between the rocks of this group. A red syenite from Nooitgedacht [748] contains 8 per cent Na_2O and 2 per cent K_2O, while a red syenite from Rhenosterspruit [609] contains 5 per cent Na_2O and 10 per cent K_2O. The high potash content of some of the syenites tends to connect them with the leucite-bearing effusive rocks, which will be mentioned below.

These red syenites bound the Pilandsberg complex on the northwestern, northern, and southeastern sides. For the greater part they are developed as a massive wall, forming the outermost circle of hills at the periphery of the mountains. The red color of the syenites has given the name to the farm Rooderand [399] and from

[1] W. A. Humphrey, "The Volcanic Rocks, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 104.

there to Saulspoort [369] the syenites form the periphery of the complex; to the south, along Ruigehoek [326], Vogelstruisnek [602], and Palmietfontein [567], they form a nearly interrupted series of bare, low hills. In the southern part, near the road from Rustenburg to Saulspoort [269], steep lujaurite hills rise from the flat norite country. In the southeastern part, where the Rhenosterspruit leaves the hills, we again see the bare, red syenite hills on both sides of the stream. Along the eastern boundary they are covered by effusive rocks. The syenites are found also in the central parts of the complex; in the southern part of Driefontein [888] numerous hills consist of these rocks. They form a conspicuous feature and from a distance can easily be distinguished from the rounded, bare, felsite ridges. We find them also in the southeastern part of Welgeval [749], on Nooitgedacht [748], Buffelskloof [219], Leeuwfontein [429], Buffelspan [585], and Houwater [496]. Near the houses on Nooitgedacht [748], in the valley of a small rivulet, light syenitic rocks with white feldspars occur, which are similar to some varieties of the rocks on Leeuwfontein [320] in the Pretoria district.

By transitions these rocks are connected with the nepheline syenites, as well as with the effusive rocks.

Diorites: As intimately associated with the foyaites and lujaurites, Humphrey[1] mentions the occurrence of diorites, which have their greatest development in the northern part of Boekenhoutfontein [889]. They are also exposed on the summit of the mountain to the southwest of the native *stadt* on Saulspoort and are found as a dike cutting through the norites on Tusschenkomst [446] to the north-northwest of the Pilandsberg complex. The rock is fine grained, has a gray color, and consists principally of augite and labradorite.

Effusive rocks: In my previous paper[2] it has been stated that porphyritic and dense equivalents of the syenites and nepheline syenites have a great development in the Pilandsberg complex. Flow structure is often beautifully developed in these rocks.

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 84.

[2] *Oorsprong en samenstelling der Transvaalsche Nepheliensyenieten*, p. 16.

The effusive rocks have recently been described in some detail by Humphrey in a paper on the volcanic rocks of the Pilandsberg.[1] He divides the rocks into two main groups—the trachytes and the phonolites. The first group contains the effusive representatives of the alkali syenites; the second group, those of the nepheline syenites. An andesitic rock was found on the ridge separating the farm Kafferskraal [890] from Saulspoort [269]. It consists of diallage, diopside, plagioclase, and iron ore in a fine-grained groundmass, and may be an effusive representative of the diorites. The rock has been classed as leucitophyre. The phenocrysts of orthoclase are accompanied by phenocrysts of leucite.

The trachytes attain their greatest development in the eastern portion of the Pilandsberg, on the farms Doornpoort [251] and Vaalboschlaagte [636], where they measure some 5,000 feet in thickness. In this succession the trachytes alternate with red "felsitic"[2] rocks and tuffs, while a thick band of leucitophyres occurs toward the base of the series. These blue-colored leucite-bearing rocks contain phenocrysts of orthoclase and leucite in a groundmass of very finely divided aegirine and feldspar. The phonolites occur in most other parts of the Pilandsberg; they are of a prevailing greenish and bluish color, contrary to the prevailing red of the trachytic series. Typical phonolites on the farm Driefontein [888] contain occasional phenocrysts of feldspar in a finely divided groundmass which consists of feldspar, nepheline, and much aegirine. In the neighborhood of Saulspoort is a rock containing phenocrysts of sodalite in a cryptocrystalline groundmass.

Volcanic breccias and tuffs are widely distributed throughout the Pilandsberg.

The effusive rocks of the isolated mountain at the boundary of Buffelspan [585], Leeuwfontein [429], and Wijdhoek [701] often have a banded appearance, and a beautiful flow structure with parallel arrangement of the feldspar phenocrysts is developed. Well-developed cubes of blue fluorine occur in some of these rocks, while Humphrey mentions the occurrence of leucite crystals. He

[1] "The Volcanic Rocks, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 105.

[2] Felsite is a field term under which Transvaal geologists comprise a great diversity of rocks: quartz porphyries, felsites, phonolites, tinguaites, andesites, etc.

found the effusives to form a thick capping resting upon the red syenites. The effusive rocks are found in the northeastern part of Buffelspan [585], in the high ridge from Houwater [496] to Wijdhoek [701], and appearing again at the other side of the Rustenburg road, where the effusives of the ridge are in contact with lujauritic rocks and can be followed in a northwesterly direction. On Tusschenkomst [331] and Welgeval [749] they are separated from the lujaurite by a shallow valley at the contact. Still more to the north we find the effusive rocks on Schaapkraal [12] and on Driefontein [888], where they are exposed in the valley of a rivulet, which flows in the direction of Rooderand [399]. On the northern farms of the Pilandsberg the high ridges of effusive rocks bend around parallel to the circumference of the complex; on the western farms they have their greatest development and almost entirely hide the deep-seated rocks.

The rocks of the country around the Pilandsberg.—The rocks which surround the Pilandsberg complex are the norites and granites of the Bushveld igneous complex and the quartzites and shales of the Pretoria series.

Norites and Pyroxenites: These rocks form the characteristic small hills (Pyramids, Zwartkoppies) parallel to the Magaliesberg range. They bend to the northwest in the neighborhood of Rustenburg, but the characteristic hills disappear long before they reach the Pilandsberg; much more to the north, on the farm Modderkuil [565], we see them again just in the continuation of those to the south of the Pilandsberg. The bands of magnetite are found to the southeast of the Pilandsberg. They end against the red syenites near the boundary of the farms Rhenosterfontein [867] and Rhenosterspruit [906], but are found again to the north of the Pilandsberg. We see that the whole southern part of the Pilandsberg is immediately surrounded by the basic rocks; on the farms Ledig [744] and Koedoesfontein [818] they are in immediate contact with lujaurites and allied rocks. Near the boundary of Zandrivierspoort [747] and Mahobieskraal [562] the isolated hills of aegirine-amphibole foyaites and the ridges of Magaliesberg quartzite come close together. At a small distance farther to the northwest and to the west the basic margin of the Bushveld com-

plex is again largely developed. It covered the whole region, which is limited to the south by the Schurvebergen and Zeerust Hills, to the west by the Marico Hills, and to the north by the Dwarsbergen.[1]

In following the basic margin along the western boundary of the Pilandsberg, we find quartzites in the northern part of Vogelstruisnek [602] which are in immediate contact with red syenites. More to the north the latter rocks border again upon norites. Near, and west of, the native *stadt* on Ruigehoek [426] norites rich in feldspars are exposed in the valley of a rivulet; they are the same rocks as those which are found to the south of the Pilandsberg, but show a pronounced schistose structure and a dip to the northeast. To the west the rocks become more basic, and near the contact with the quartzites on Davidskuil [142] very basic rocks were collected in the valley of a rivulet which is crossed by the road from the native *stadt* on Mabieskraal [620] to Janskop on Bierkraal [545]. They, too, show a pronounced schistose structure. Here the strike is about N. 15 W., and the dip is to the east-northeast.

On Tusschenkomst [446], to the east of the quartzite hill Janskop on Bierkraal [545], a series of hills consisting of schistose basic rocks can be followed in a north-northwesterly direction. Humphrey[2] mentions a peculiar feature of the pyroxenites, particularly noticeable on the farms Ruigehoek [426] and Zandspruit [181], where narrow bands of chromite, dipping to the east, have formed a band of comparatively high ground and an apparent stratification.

From all that has been said above, it is evident that the basic margin of the plutonic complex *is cut off abruptly* by the intrusion of the Pilandsberg.

Granites: The red granites of the igneous complex of the Bushveld are found to the east of the norites. The boundary between the two rock types crosses the Elands River in the southeastern part of Rhenosterfontein [867] and ends against the alkali syenites. The red granites are found all along the eastern part of the Pilandsberg; on Saulspoort [269], west of the Rustenburg road, the

[1] F. H. Hatch, *Trans. Geol. Soc. South Africa*, VII (1904), p. 1.

[2] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 81.

boundary between the norites and granites begins against the effusive rocks of the Pilandsberg complex and runs from there in a northeasterly direction. The occurrence of brecciated rocks with granite boulders in the hill behind the Saulspoort Mission station, which was already mentioned in my previous paper, has been studied in detail by Humphrey,[1] who found various types of igneous rocks. The relationship between these is very complicated. Syenite is seen to be intrusive into the effusive rocks and fragments of granite are found within the syenites and effusive rocks. Farther up the hill there is an extensive outcrop of granite which extends for some 800 yards along the face of the hill. Above this granite is found a diorite, and the crest of the hill is formed by effusive rocks. Breccias, in which granite occurs as included boulders, and also repeated outcrops of granite were found on Doornpoort [251] and Zuiverfontein [718] in the eastern marginal part of the Pilandsberg. Large boulders of red granite embedded in coarse red syenite are to be seen in the bed of the Rhenosterspruit on the farm Rhenosterspruit [609].

Pretoria series: The Magaliesberg Range, which from Rustenburg strikes in a northeasterly direction, comes to an abrupt end on Mahobieskraal [567], to the southeast of the Pilandsberg complex. Then the Pretoria beds bend to the west; near Bechuanaland they have a short northerly direction, and then return again to the east, passing at a distance of about 8 miles to the north of the Pilandsberg complex and forming the northern boundary of the igneous complex of the Bushveld.

Isolated hills of quartzite are found at several places to the east of the Pilandsberg. On Vogelstruisnek [602] they are in immediate contact with the red syenites. Other hills of quartzite occur on Tweelaagte [180], Vlakfontein [902], behind the native *stadt* on Mabieskraal [620], on Davidskuil [142], and still more to the north on Bierkraal [545]. From Janskop on Bierkraal the quartzite hills extend still more to the east, where they approach the northern boundary of the igneous complex of the Bushveld.

Between the Pilandsberg and the Marico River, the Upper Magaliesberg beds are missing from the normal sequence of the Pretoria series. They are represented by the isolated hills of

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 87.

quartzite, which are entirely surrounded by rocks belonging to the igneous complex of the Bushveld and most probably were broken up in connection with the intrusion of this complex.

Dike rocks.—The first nepheline syenite of the Transvaal was discovered by Elie Cohen[1] in 1872, near the Hex River, between Renseburg and Rustenburg. He states that this rock forms the lower parts of the Zwartkoppies, where these hills bend to the northwest. The rocks collected by Cohen were described by E. A. Wülfing[2] in 1886 as porphyritic foyaites in which the nepheline only occurs in the groundmass.

In 1904 G. A. F. Molengraaff[3] collected nepheline syenites on the farms Elandsheuvel [255] and Tweede Poort [189]; these rocks are porphyritic foyaites in which nepheline occurs as phenocrysts. These rocks are described in the petrographical part of my previous paper. Since that time the sheet Rustenburg (sheet No. 4) has been mapped by the Geological Survey of the Transvaal, and it is shown that several dikes of these porphyritic foyaites intersect the rocks of the Bushveld complex, running from the Pilandsberg in a southeasterly direction.

Some of them even cut through the Magaliesberg Range to the east of Rustenburg and can be followed still farther to the south.

A fine-grained red syenitic rock was found by me to the north of the red hill on Rooderand [399], cutting through the norites in a nearly northerly direction. At the boundary of Groenfontein [302] and Bierkraal [545] near the quartzites, a porphyritic syenite was found in the basic rocks. On Plate XIV in the annual report for 1911 of the Geological Survey of South Africa it is shown that several syenitic dike rocks can be followed from the Pilandsberg in a north-northwesterly and northwesterly direction.

All these dikes cut through the norites and granites of the Bushveld, *and they have been intruded after the consolidation of the rocks of the Bushveld igneous complex.*

[1] E. Cohen in *Berichte über die XVI. Versammlung des Oberrheinischen Geologischen Vereins*, am 29 März, 1883, Stuttgart.

[2] E. A. Wülfing, "Untersuchung eines Nephelinsyenits aus dem mittleren Transvaal," *Neues Jahrb. f. Min. Geol. u. Pal.*, 7 Mai, 1888, Bd. II, p. 16.

[3] G. A. F. Molengraaff, "Preliminary Note on the Geology of the Pilandsberg," *Trans. Geol. Soc. South Africa*, VIII (1905), 208.

Inside the Pilandsberg several dikes occur. Some dike rocks with the macroscopic appearance of the tinguaites form a band of comparatively high ground, because of their resistance to denuding agencies. On Boekenhoutfontein [889] near the boundary with Kafferskraal [890] a dike of this kind strikes N. 50 W.; it measures about 10 meters across and cuts through the foyaites with biotite; the contact with the foyaites is formed by a bent line, as well as the contact of a dike in the southeastern part of Koedoesfontein [649].

Near the boundary of Driefontein [889] and Nooitgedacht [148] I found a tinguaitic dike, 2 meters in diameter, with a sharp contact and a northeasterly strike, cutting through medium-grained nepheline syenites in the valley of a rivulet. Near the contact the rock has a glassy appearance; in the central part the structure is porphyritic. This dike dips steeply to the northeast. At the boundary of Olivenfontein [145] and Rooderand [398], in the valley to the south of the red syenites, a similar dike, which measures 5 meters across, is exposed.

The direction of these dikes agrees nearly with that of the dikes outside the Pilandsberg. In the western rivulet to the north of the houses on Driefontein [888], a tinguaitic dike or segregation, averaging 40 centimeters in width, has a blended contact with the surrounding lujaurites. It is rich in bronze-brown flakes of mica. Near the lujaurites the rock is very rich in aegirine; this mineral is often developed in spherulites which are up to 1 centimeter in diameter.

According to Humphrey,[1] dikes of foyaite, red syenite, nepheline syenite, and diorite occur in all parts of the Pilandsberg, and, in addition to these, there are many basaltic and tinguaitic varieties occurring in various parts. In the spruit on Saulspoort [269] a dike of red syenite cuts through the effusive rocks. A series of red "felsitic" dikes and blue-black glassy dikes, which were difficult of determination, and dikes of nepheline syenite traverse the red syenites. The dikes of nepheline syenite, which have their greatest development outside the Pilandsberg, seem to disappear into the

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 85.

nepheline syenites in the central part of the complex. Dikes of foyaite were found traversing the red syenites of the central part.

From all that has been said above, it is evident that *the foyaites are the youngest rocks* of the Pilandsberg complex, while there is good evidence to show that the red syenite is older than some of the effusive rocks.

Pegmatites.—Dikes of pegmatite, which in many other nepheline syenite regions contain numerous rare minerals, were not met with during my visit. Coarse-grained pegmatitic segregations in the normal-grained rocks are of frequent occurrence, but the rare minerals were not found in much larger crystals than in the normal-grained varieties.

Pegmatites rich in eucolite are well exposed in lujauritic rocks from the hills to the north of the houses on Driefontein [888]. They consist principally of large crystals of feldspar, green nepheline, long crystals of aegirine, and carmine-red eucolite which is partly altered to catapleiite; they also contain some astrophyllite. The prisms of aegirine are up to 10 centimeters in length, and sometimes show a graphic intergrowth with feldspar. Near, and to the west of, the main road to Saulspoort [269] where it crosses the Rhenosterspruit in the northeastern part of Buffelspan [585], we found pegmatites in the aegirine-amphibole foyaites. Feldspars up to 10 centimeters in length, green nepheline, prisms of amphibole, and prisms or spherulites of aegirine are the main constituents; they also contain some fluorine. Amphiboles with a very small angle of optic axes *in which the plane of the optic axes is normal to the plane of symmetry*[1] occur in these rocks. In the southern part of Wijdhoek [701], near, and to the west of, the main road and to the south of the ridge of effusive rocks, we found pegmatites, which are very rich in astrophyllite and spherulites of aegirine, measuring up to several centimeters in diameter. They are found still farther to the southwest on Koedoesfontein [746] in a rivulet which joins the Wolvespruit, where numerous blocks of pegmatites and lujaurites could be collected; some of them are very rich in eucolite.

[1] H. A. Brouwer, "On Zonal Amphiboles in Which the Plane of Optic Axes of the Margin Is Normal to That of the Central Part," *Proceed. Kon. Akad. Amsterdam*, XVI (1913), 275.

The aegirine-biotite foyaites in the northwestern part of Boekenhoutfontein [889] contain pegmatitic segregations and small dikes in which feldspars, feldspathoids, and eucolite mineral and small pale-yellow needles occur. Often they are very rich in aegirine; this agrees with its tardy crystallization in most of the rocks of the region.

Finally, we found segregations in the lujaurites to the west of the common boundary post of Tusschenkomst [331], Leeuwfontein [429], and Wijdhoek [701]; they consist almost entirely of aegirine spherulites which are up to some centimeters in diameter.

Segregations rich in fluorine occur in the microfoyaites of Olivenfontein [745], and segregations rich in large aegirine spherulites occur in mesocratic foyaites of the valley, running in a north-south direction in the northeastern part of Buffelspan [585].

Humphrey mentions the occurrence of very coarse-grained pegmatites with much fluorspar on Doornhoek [134] and beautiful pegmatites, about half a mile from the homestead on Driefontein [888] on the main road to Buffelskloof (219).

Mechanism of intrusion of the Pilandsberg complex.—Since the rocks of the Pilandsberg complex are younger than the red granites and norites of the Bushveld igneous complex, and since the Pilandsberg is surrounded on three sides by norites and on one side by red granites, it seems to be beyond doubt that the space which is occupied by the Pilandsberg intrusive rocks was occupied, prior to the intrusion, by the norites and red granites of the Bushveld.

That the removal of the original rocks was not the result of folding is proved by the occurrence of a great number of vertical dikes of vast extension, which are genetically connected with the intrusion.

The hypothesis that the subsidence of crust blocks elsewhere was the cause of the intrusion of the magma and the hypothesis of laccolithic intrusion seem not to be applicable in the present case.

As has been stated by Humphrey, there can be no doubt that the Pilandsberg represents the remnant of what was once an important focus of eruption, and the hypothesis that the intrusive magma has filled up the cavities which were formed by volcanic outbursts of an explosive character seems to be applicable.

Tuffs and volcanic breccias are found all over the areas where the effusive rocks are developed. The main rock types of the Pilandsberg are disposed in concentric circles, of which the outermost consists of syenites and nepheline syenites and is followed toward the center by a ring of effusive rocks. The latter dip, with a few local exceptions, from the center outward, and the highest hills formed by intrusive rocks in the central area of the complex still carry a capping of volcanic rocks which have resisted denudation.

If the Pilandsberg is considered as the remnant of what was once a volcano and its subsidiary peripheral vents, this must have been of stupendous dimensions, since the intrusive rocks cover a surface whose diameter varies from 15 to 18 miles, the lavas having extended far beyond the periphery of the intrusives.

It is peculiar that in the territory of the Pilandsberg effusive rocks are found in large quantity between the granular rocks, whereas they do not occur in the surrounding granites and norites. The lavas, which must have extended far beyond its periphery, have entirely disappeared and do not even cap the hills of Magaliesberg quartzite, though at some places the quartzite is found in the immediate neighborhood of the Pilandsberg. It is very likely that in connection with the intrusion of the alkali rocks the roof has locally sunk down, and, while it has disappeared everywhere else in the neighborhood by erosion, we see the remains preserved just on those spots where the roof has given way.

Subsidences in ancient volcanic regions are by no means rare. Judd,[1] for instance, mentions the comparatively perfect state of preservation exhibited by the great volcano of Mull, if compared with that of the other great Tertiary volcanoes in the Hebrides. It can be shown that this difference is due to a central subsidence which took place in the Mull volcano. From the sections along the shores of the deep fiords it is evident that the basaltic lava sheets dip toward the central mass of eruptive rocks, the inclination increasing as we approach the volcano. Further, there is clear

[1] J. W. Judd, "On the Ancient Volcanoes of the Highlands and the Relations of Their Products to the Mesozoic Strata," *Quart. Journal of the Geol. Soc.*, XXX (1874), 256.

evidence of the existence of faults, the downthrow of which is in all cases toward the great central mass. A similar subsidence took place after the period of the eruption of acid lavas and before that of the basaltic lavas.

The state of preservation of the Pilandsberg complex and surrounding area is not very favorable to a study of the amount of subsidence in the sunken area. The lavas, which must have extended far beyond the mountain proper, have entirely disappeared; the junction of the intrusive rocks of the Pilandsberg with those of the Bushveld is not well exposed; and the amount of denudation in the area surrounding the complex cannot be estimated. This probable subsidence and the large dimensions of the plutonic body lead us to mention another hypothesis to explain the mechanism of intrusion of many batholites, which has been set forth by Daly.[1] He termed this process "overhead stoping"; it consists of a continued breaking free of roof blocks and a sinking down of the detached blocks into the magma, which consequently rises and occupies the place of the sunken fragments.

The cover of the intrusive rocks of the Pilandsberg entirely consists of lavas, the effusive equivalents of the intrusive rocks, and this is very common in batholitic intrusions from other parts of the world. How these facts are explained by overhead stoping has been elaborately discussed by Ussing[2] in a recent treatise on the geology of the country around Julianehaab. If a batholitic magma on one or more occasions during its intrusion has penetrated its cover, this will presumably lead to a volcanic outburst of catastrophic character, accompanied by the outpouring of lava flows and followed by a period of quiescence. After a time, when hot magma from below is brought into contact with the newly formed roof, the stoping process will continue, interrupted by few volcanic outbursts until the magma has cooled to its point of solidification.

In several batholites with a permanent cover of sedimentary rocks the stoping process came to an end and the magma was

[1] R. A. Daly, "Geology of the Ascutney Mountain," *Un. St. Geol. Surv. Bull. No. 209* (1903), p. 93; "The Mechanics of Igneous Intrusion," *Amer. Jour. of Science*, 4th series, XV (1903), and XXVI (1908).

[2] N. V. Ussing, "Geology of the Country around Julianehaab, Greenland," *Medd. om Grönland*, XXXVIII (1911), p. 302.

solidified before the earth's surface was reached, but the Pilandsberg alkali magma must have been very rich in mineralizing agents, which reduced its viscosity, and in such magmas the stoping process may go on when they near the earth surface and until the cover is penetrated. Volcanic outbursts cause an escape of the volatile substances, and the magma becomes more and more viscous, until a new supply of heat and mineralizers from below sets up stoping again. In fact, several rare minerals with a highly complex constitution, which are not stable at high magmatic temperatures, occur within the Pilandsberg rocks. Fluorine is a very common constituent, and, as their very name imports, fluorides must have reduced the viscosity considerably. Moreover, fluorine and other minerals in which we find direct evidence of the co-operation of mineralizers are regularly distributed in several rocks of this region, where they crystallized in the last cavities, thus proving that the mineralizing agents in part were regularly distributed until the final consolidation.

Of course, direct support would be given to the co-operation of overhead stoping if fragments which could only be derived from an original cover of the crystalline rocks were found among the rocks of the Pilandsberg complex, but Humphrey[1] mentions that all the close-grained rocks, which in the hand specimens very much resemble shales, proved themselves under the microscope to be devitrified lavas.[2] Particularly at those places in the northeastern part of the area where the granites are found to within a few hundred yards of the Pilandsberg complex it is of great interest to know whether these granites occur in their original position.[3]

Age of the Pilandsberg.—In the neighborhood of the Pilandsberg the rocks which formed the covering of the igneous complex of the Bushveld at the time of its intrusion most probably belonged to the

[1] "The Volcanic Rocks of the Pilandsberg, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 102.

[2] In my previous paper (*Oorsprong en samenstelling der Transvaalsche Nephelien-syenieten*), p. 17, I mentioned having found shales in the valley to the north of the homestead on Houwater [496], but the rocks were not studied under the microscope.

[3] Cf. also H. A. Brouwer, "On the Formation of Primary Parallel Structure in Lujaurites," *Proc. Kon. Akad. Amsterdam*, 1912, p. 734.

Waterberg system; they have here been entirely removed by denudation. Humphrey mentions that there are no signs of the presence of Waterberg rocks among the stratified lavas, nor were any fragments of those rocks found among the volcanic breccias, while many examples of included granite boulders within the Pilandsberg rocks were found.

He concludes that the volcanic outbursts and the outpouring of lava postdated the removal of all of the sedimentaries of the Waterberg system in this neighborhood. No evidence is available about the age of the Pilandsberg rocks with regard to the Karroo system.

Of course, if the possibility of overhead stoping is admitted, the problem of the age of the Pilandsberg rocks is more complicated, but the question of the mechanism of intrusion is still too vague for further discussion.

OTHER OCCURRENCES OF NEPHELINE SYENITES AND ALLIED ROCKS

The occurrence of nepheline syenites on Leeuwfontein [320] and Zeekoegat [287] was discovered by Molengraaff in 1898.[1] The numerous variations of the Leeuwfontein foyaites in chemical and mineralogical composition and also the leucocratic and melanocratic dike rocks, bostonites, monchiquites, tinguaites, etc., were described. Liebenerite porphyries, like those which occur at Predazzo in the Tyrol and at Alnö (Sweden), are also associated with the nepheline syenites of this region.

D. Draper discovered nepheline syenites on Walmansdal [116] to the northwest of Zeekoegat [287]. The rocks to which J. A. L. Henderson[2] gave the name hatherlite were also collected on Leeuwfontein [320]. As was stated by Molengraaff,[3] the name hatherlite is not applicable because the old powder factory "Eerste fabrieken" or "Hatherley factory" is situated to the south of the Magaliesberg Range and has nothing to do with the factory on Leeuwfontein [320].

[1] G. A. F. Molengraaff, "Note on Our Present Knowledge of the Occurrence of Nepheline Syenite in the Transvaal," *Trans. Geol. Soc. South Africa*, VI (1903), p. 89.

[2] J. A. L. Henderson, *On Certain Transvaal Norites, Gabbros, and Pyroxenites and Other South-African Rocks*, London, 1898.

[3] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 46.

In the *Annual Report of the Geological Survey of the Transvaal* for 1903, A. L. Hall[1] gives an account of the rocks from Leeuwfontein [320] and Zeekoegat [287] which is followed by a petrographical description of these rocks and those on Walmansdal [116] and the newly discovered occurrence on Franspoort [426].

On Leeuwkrall [396], about 5 km. to the northwest of Hamanskraal station, H. Kynaston[2] discovered two occurrences of syenitic rocks, the southern one locally graduating into nepheline syenite. It is a porphyritic foyaite similar to some of the dike rocks which occur to the southeast of the Pilandsberg. On Rietfontein [451] and Spitskop [463] an interesting occurrence of nepheline syenites within the red granites was discovered by Hall[3] in 1910; and Wagner[4] mentions the occurrence of a dike of basic camptonite cutting through the Waterberg sandstones on Buffelspruit [1920], which means probably that nepheline syenites occur at a deeper level.

The intrusion on Leeuwfontein [320].—To the east of Pretoria, near Franspoort [426], the ridges of quartzite belonging to the Pretoria series bend to the southeast; the Magaliesberg quartzites have been extended in length, while the Daspoort and Timeball quartzites were strongly pressed in a direction slightly oblique to the strike of the strata.

In describing the dislocations connected with the intrusion of the igneous complex of the Bushveld, Molengraaff[5] supposed that at those places where the circumference of the complex shows a convex curve interesting phenomena may be expected. We saw that the Pilandsberg intrusion is located where the Pretoria series,

[1] A. L. Hall, "On the Area to the North of the Magaliesberg Range and to the East of the Pietersburg Railway Line," *Annual Report of the Geol. Survey of the Transvaal*, 1903, p. 38.

[2] H. Kynaston, "On the Area Lying North-West of Pretoria, between the Magaliesberg Range and the Salt Pan," *Annual Report of the Geol. Survey of the Transvaal*, 1905, p. 29.

[3] *Annual Report of the Geol. Survey of the Transvaal*, 1910.

[4] P. A. Wagner, "Note on an Interesting Dyke Intrusion in the Upper Waterberg System," *Trans. Geol. Soc. South Africa*, 1912.

[5] G. A. F. Molengraaff, *Proc. Geol. Soc. of South Africa*, 1905; "Criticism on Messrs. A. L. Hall and F. A. Steart: On Folding and Faulting in the Pretoria Series," *Trans. Geol. Soc. South Africa*, VIII (1905), 7–15.

which from Rustenburg strike in a northeasterly direction, bend again to the west, and the nepheline syenite intrusions to the northeast of Pretoria are found where the ridges of quartzite bend to the southeast. The foyaite intrusion on Franspoort [426] is entirely surrounded by Magaliesberg quartzite and is clearly intrusive in them. Near the intrusion on Leeuwfontein [320], which borders "felsites" only on the north, the Magaliesberg quartzites cover a large surface in consequence of numerous faults. Following the valley of the Pienaars River to the north, we see a succession of red "felsites" with an approximate east-west strike and a varying dip to the north, alternating with eruptive breccias, conglomerates, and basic effusive and dike rocks. More to the north, on Roodeplaat [314], they are covered by shales and syenitic rocks of doubtful age, and on Paarderfontein [338], at a great distance from the foyaite, dikes of tinguaitic and andesitic character, which in part are connected with the intrusion on Leeuwfontein [329], cut through the sandstones and conglomerates of the Waterberg system. The chemical composition of a tinguaite of Paardenfontein [338] closely agrees with that of the normal foyaites on Leeuwfontein [320]. The small differences are similar to those which characterize the nepheline syenites and accompanying tinguaite dikes from other regions.

An interesting dike of basic camptonite has recently been described by Wagner.[1] It occurs on Buffelspruit [1920] in the Waterberg district and cuts through Waterberg sandstone. This proves again that the intrusion of nepheline syenite with which the dike most probably is connected is younger than the Waterberg sandstones.

The "felsites" are the effusive equivalents of the intrusive rocks on Leeuwfontein [320]. The liebenerite porphyries, which in the southern part of Roodeplaat are exposed over a long distance in the valley of the Pienaars River, show the same characteristics as the liebenerite porphyries of Alnö and the Tyrol. But also the dense weathered rocks of which the mineralogical composition could not be recognized under the microscope belong to the alkali

[1] P. A. Wagner, "Note on an Interesting Dyke Intrusion in the Upper Waterberg System," *Trans. Geol. Soc. South Africa*, 1912.

rocks, as was proved by chemical tests. After treating the powder with hydrofluoric acid, only 0.4 of its weight was evaporated, and a simple calculation makes evident that the Al partly occurs in feldspars, partly in feldspathoids. Microchemically the residue gave a strong soda reaction and a very feeble potash reaction. From this it is evident that "felsites" which are the effusive equivalents of the intrusive rocks are genetically connected with the alkali rocks of the intrusion on Leeuwfontein [320].

An exact petrographical examination will greatly assist in the determination of the stratigraphical place of the different "felsites." Identity in age for the felsophyres of the Waterberg district and of the phonolites of Leeuwfontein [320] would seem to be in the highest degree improbable.

From a petrographical point of view there is much resemblance between the rocks of Leeuwfontein [320] and those of the Pilandsberg; the association of foyaites of varying composition with red syenites and effusive rocks is a common characteristic. The rocks on Leeuwfontein [320] near the old dynamite factory are principally red syenites and red hololeucocratic feldspar rocks; in the southern part the *leeuwfonteinites* with accompanying porphyritic equivalents occur. The porphyritic rocks sometimes form well-defined dikes.[1] Leeuwfonteinite porphyry and monzonite porphyries are found between Leeuwfontein [320] and Franspoort [426] and along the path to Derde Poort [469]. The numerous varieties of foyaite occur near the boundary of the farms Leeuwfontein [320] and Zeekoegat [287]; they will be described in detail in a forthcoming petrographical paper. The normal foyaite of this region is a coarse-grained, leucocratic, aegirine-amphibole foyaite. In varieties rich in feldspathoids (particularly sodalite) aegirine is the only dark constituent; they pass into rocks which are nearly free from feldspar (*tawites*). Rocks very rich in titanite (*pienaarites*) occur at several places. The rocks on Leeuwfontein [320] differ from those of the Pilandsberg by the absence of rare minerals in the latter rocks. In other nepheline-syenite regions the rare minerals are

[1] The leeuwfonteinites are the same rocks as Henderson's hatherlites (anorthoclase syenites), cf. Henderson, *On Certain Transvaal Norites, Gabbros, and Pyroxenites and Other South-African Rocks*. They contain much plagioclase and their composition varies between that of the alkali monzonites and that of the alkali syenites.

also often limited to the aegirine foyaites and the arfvedsonite foyaites and are wanting in the foyaites with barkevikitic amphibole. The rare minerals and a not very small quantity of lime in the magma seem to exclude one another (compare the analysis of the normal foyaite of Leeuwfontein, which has been given in my previous paper). The association of foyaites with leeuwfonteinites which besides barkevikite also contain plagioclase makes it probable that the CaO content of the common mother-magma was rather considerable.

The rocks of the neighborhood of Leeuwfontein [320], which hitherto have been studied under the microscope, belong to the following groups:

1. Aegirine foyaites
   Leucocratic rocks
   Pienaarites (melanocratic rocks rich in titanite)
2. Aegirine-amphibole foyaites
3. Tawites
4. Feldspar rocks
5. Aegirine-foyaite porphyries
6. Aegirine-amphibole foyaite porphyries
7. Leeuwfonteinites
8. Leeuwfonteinite porphyry and monzonite porphyry
9. Tinguaite porphyries
10. Monchiquites
11. Augitites
12. Andesitic camptonites
13. Doleritic nepheline basalts
14. Diabases
15. Liebenerite porphyries
16. Bostonites
17. Phonolites

H. Kynaston[1] mentions that *the foyaite of Walmansdal* [116] is clearly intrusive in the "felsites."

Nepheline syenite region to the west of Lydenburg.[2]—This region covers a surface which has about the same extension as that on Leeuwfontein [320]. It is surrounded by red granites and occurs

[1] H. Kynaston, "The Geology of the Country Surrounding Pretoria," Explanation Sheet I, *Geol. Surv. of the Transvaal*, 1907, p. 28.

[2] A. L. Hall, in *Annual Report Geol. Surv. of the Transvaal*, 1910.

close behind the zone of ultra-acid rocks which Hall discovered at the boundary between the granites and the basic margin of the igneous complex of the Bushveld. The specimens which Mr. Hall kindly put at my disposal during my stay in the Transvaal are melanocratic lujaurites and lujaurite porphyries, which sometimes show a schistose structure. The colorless minerals are sometimes very subordinate and microscopically the rocks seem to consist almost wholly of fine needle-shaped crystals of aegirine. These very melanocratic lujaurites were rare in the Pilandsberg complex, but seem to cover the greater part of this newly discovered occurrence.

Foyaites also occur, and it is interesting to find the association of lujaurites with leucocratic feldspathoid rocks (*urtites*), which consist chiefly of nepheline. The association of lujaurites and urtites in the peninsula of Kola (they received their names from the same place—Lujavr Urt) is also a characteristic of this district.

An isolated mass of strongly metamorphic limestone is inclosed within the alkali rocks.

ORIGIN AND AGE OF THE NEPHELINE SYENITES AND ALLIED ROCKS

It does not seem improbable that the nepheline syenites have originated from the same sources as the granites and norites of the Bushveld. The formation of the basic margin in the main intrusion of the Bushveld proves that magmatic differentiation took place on a very large scale. Toward the periphery the rocks become more and more basic, while granites occupy the central portion. When tested in detail, the view of general increase of basicity from the center toward the periphery requires modification. Hall[1] has described a zone of ultra-acid rocks with 97 per cent SiO_2 in the red granites close to the boundary with the norites to the west of Lydenburg. He considers these rocks as a product of extreme differentiation, which could take place near the basic margin, when the viscosity of the granitic magma was already strongly increased. That sometimes the acid and basic rocks pass gradually into one another possibly depends on the depth to which the complex has been exposed by erosion.

[1] A. L. Hall, "Note on Certain Widespread Ultra-Acid Rocks Occurring along the Margin of the Bushveld Granite, etc.," *Trans. Geol. Soc. South Africa*, XIII (1910), p. 10.

If ultra-acid rocks have differentiated from the granitic magma, the residual magma will be enriched in Al_2O_3, and alkalies with regard to SiO_2 and its composition will more or less agree with that of the nepheline syenites. This kind of differentiation may have taken place on a much larger scale at a greater depth, which has not been exposed by denudation. It is interesting to find an occurrence of nepheline syenites on Rietfontein [451] and Spitskop [463], close behind the zone of ultra-acid rocks.

The coarse textures, the rather indefinite order of crystallization, the numerous poikilitic structures,[1] the abundance of fluorine and rare minerals with a highly complex constitution, which are characteristic for many of the nepheline syenites in the Transvaal, make it probable that these rocks crystallized from a residual magma in which the volatile constituents were concentrated and which may have crystallized at rather low temperatures. Some of the nepheline syenites are certainly younger and may be considerably younger than the sandstones and conglomerates of the Waterberg system; the time at which the different intrusions have risen to the present level and the time at which they have consolidated may have varied between wide limits.

The age of an intrusive rock is determined by the time of its consolidation, and it is very probable that the alkali magmas remained fluid during a very long period of igneous activity. When these magmas which are rich in volatile substances shall crystallize will greatly depend upon the eventual loss of these substances, which may have been the immediate cause of crystallization quite as much as of any actual cooling.[2]

Only some characteristic features of the various igneous rocks have been dealt with; as has been stated above, it does not seem improbable that the nepheline syenites and allied rocks have originated from the same sources as the granites and the norites of the Bushveld. To the petrologist there are many very interesting problems with regard to the origin and age of the different rock types which would repay further research.

[1] H. A. Brouwer, "On Peculiar Sieve Structures in Igneous Rocks Rich in Alkalies," *Proc. Kon. Akad. Amsterdam*, November, 1911.

[2] A. Harker, *The Natural History of Igneous Rocks*, 1909, p. 186.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

FLETT, J. S., and HILL, J. B. *The Geology of the Lizard and Meneage*. Mem. Geol. Surv., Sheet 359. London, 1912. Pp. 280, pls. 15, figs. 10, bibliography 10 pp.

The rocks of the Lizard, probably of Archean age, represent an igneous complex of serpentine, gabbro, and gneiss, surrounded by an aureole of hornblende-schists and metamorphosed sedimentary rocks—mica-schists, green-schists, and quartz-granulites. The hornblende-schists were originally basic igneous rocks, but they are now so much altered that their original character as extrusive, tuff, or intrusive cannot be determined in every case. Some of them contain sedimentary material and possibly represent volcanic ashes. The time that elapsed between the formation of the schists and the intrusion of the serpentine is not known, but most of the rocks of the aureole probably were already in a metamorphosed condition at the time of the intrusion of the basic rock. Besides the serpentine there is also a coarse hornblende-schist in some places, which may represent dolerite sills intruded immediately before the basic rock.

Numerous chemical analyses and photogravures of thin sections make the memoir a valuable work for reference. It is a notable contribution to the literature of serpentine.

FLETT, J. S. "The Geology of the Lizard," *Proc. Geologists' Assoc.*, XXIV (1913), 118–33, pls. 3, map 1.

A brief summary of the preceding paper on the geology of the Lizard, intended for the use of members of the Geologists' Association on their Easter excursion, 1913.

FLETT, J. S., and HILL, J. B. "Report of an Excursion to the Lizard, Cornwall," *Proc. Geologists' Assoc.*, XXIV (1913), 313–27, pls. 4.

FOYE, WILBUR G. "Nephelite-Syenites of Haliburton County, Ontario," *Amer. Jour. Sci.*, XL (1915), 413–36, figs. 9.

The nephelite-syenite laccoliths of Haliburton County, central Ontario, are described together with the associated rocks. A number

of analyses with recomputations in the C.I.P.W. system are given. Among the rocks are syenite, canadite, nephelite-pegmatite, various contact rocks, hornblende-nephelite rock, monmouthite, biotite-nephelite rock, and pegmatitic nephelite-syenite. The writer thinks that the close association of the granite-pegmatite with the nephelite-syenite indicates that they originated from a primary granite magma at about the same time. Following Daly, he thinks that the nephelite-syenites were produced by the action of limestone on the granite magma.

GOLDMAN, MARCUS I. "Petrographic Evidence on the Origin of the Catahoula Sandstone of Texas," *Amer. Jour. Sci.*, XXXIX (1915), 261–87, figs. 12.

Thinks the Catahoula sandstone originated from wind-blown sand in an arid region. The arrangement of fossils indicates subaërial burial in blown sand in some cases, and burial by wind, but in a quiet body of water, in others. Evidence for the interpretation of disintegrated sediments in general is considered in detail.

KATO, TAKEO. "Mineralization in the Contact Metamorphic Ore Deposits of the Ofuku Mine, Prov. Nagato, Japan," *Jour. Geol. Soc. Tokyo*, XX (1913), 13–32, pl. 2, figs. 3.

The copper ores of the Ofuku mine are contact metamorphic deposits in sedimentary rocks at a short distance from an igneous body. They are accompanied by typical contact minerals, such as wollastonite, garnet, vesuvianite, etc., which were deposited metasomatically from solutions derived from the igneous magma. The character of the solutions changed gradually during the period of metamorphism. At first they were very siliceous; later they became more basic, and rich in iron and silica and with more or less sulphide ores, and finally very basic and rich in copper and iron sulphide and poor in silica.

KOTO, B. "On the Volcanoes of Japan," *Jour. Geol. Soc. Tokyo*, XXIII (1916), 1–13, 17–28, 29–55, to be continued.

These three papers represent the beginning of a series of articles by Doctor Koto on the Japanese volcanoes. Of the 170 post-Tertiary volcanoes of Japan, 55 are active. All the recent lava is andesitic, but some of the earlier flows were plagioliparite and basalt. The writer describes each volcano in brief form, classifying the cones according to the system proposed by Schneider, and gives references to previous work.

Kozu, S. "Petrological Notes on the Igneous Rocks of the Oki Islands," *Science Repts. Tokoku Imp. Univ., Sendai, Japan.* Second Series, Vol. I (1913), No. 3, 25–56, pls. 4, figs. 5.

The Oki Islands lie about 65 kilometers off the coast of Honshu, on the Korean side. They consist mainly of volcanic rocks extruded between the middle of the Tertiary and the beginning of the Pleistocene, and lie upon or were intruded into the Tertiary beds which form the base of the islands. The succession of the igneous rocks cannot be exactly determined in all cases but it appears to be as follows, beginning with the most recent:

10. Holocene sediment, a river deposit of limited extent in valleys
9. Trachydolerites and basalts
8. Pleistocene (?) deposits
7. Trachytic rocks
6. Trachydolerites
5. Banded alkalic rhyolites
4. Alkalic rhyolites
3. Quartz-syenites and schistose granitic rocks
2. Andesites
1. Tertiary deposits

The various rock-types are described in detail, chemical analyses are given for most of them, and the names in the C.I.P.W. system are determined.

Reviews

Physiography of the Beaverdell Map-Area and the Southern Part of the Interior Plateaus of British Columbia. By LEOPOLD REINECKE. Geol. Surv., Canada, Museum Bull. No. 11, 1915. Pp. 58, pls. 5, figs. 3, map 1.

A study of the Beaverdell area is of value because its history is characteristic of the whole plateau region of British Columbia. Following the eruption of lavas (Nipple Mt. series) in early Miocene a mature topography was developed. Late in the Tertiary the canyon-cutting stage was inaugurated by an uplift of about 1,000 feet. Pliestocene glaciation, first by continental ice from the north and later by valley glaciers, modified the youthful topography. The present areal ratio of uplands to valleys is three to one.

H. R. B.

Report on the Copper Deposits of the Eastern Townships of the Province of Quebec. By J. AUSTEN BANCROFT. Dept. of Colonization, Mines and Fisheries, Mines Branch, 1915. Pp. 295, pls. 10, figs. 9, map 1.

Lenticular bodies of pyrite carrying a little chalcopyrite occur in highly metamorphosed igneous and sedimentary rocks. A large proportion of the deposits have been formed by irregular impregnation and replacement along shear zones within altered igneous rocks. Other deposits occur at the contacts of the intrusives and as impregnations or partial replacements of limestones. The schistose intrusives seem to have been the source of the sulphide ores.

Development in this region was begun during the Civil War, when the price of copper was abnormally high. Since 1869 only a few companies have operated. Four properties have yielded large profits; no others have repaid the money spent upon them. The future development of the mines depends largely on the utilization of the sulphur content of the ores in the manufacture of sulphuric acid, or other chemicals.

H. R. B.

Notes on the Geology and Paleontology of the Lower Saskatchewan River Valley. By E. M. KINDLE. Geol. Sur., Canada, Museum Bull. No. 21, 1915. Pp. 25, pls. 4.

Description of Silurian sections and faunas, including new species, *Leptaena sinuosus* and *L. Parvula.*

H. R. B.

The Geology and Mineral Resources of the Buller-Mokihinui Subdivision, Westport Division, New Zealand. By P. C. MORGAN and J. A. BARTRUM. New Zealand Dept. of Mines, Geol. Surv., Bull. No. 17, new series, 1915. Pp. 210, pls. 19, figs. 1, maps 9.

This area is situated on the northeast coast of the South Island of New Zealand. The rocks are described as consisting of the Aorere series of metamorphosed Siluro-Ordovician sediments intruded by pre-Triassic granites, a coal-bearing Eocene series, the Oamaru series of Miocene age, and Quaternary deposits, both Pleistocene and Recent.

The Westport district is famous for its gold placers, fluvial and marine gravels having yielded a total of £4,675,000. The industry has greatly declined in recent years. The Eocene coal is a high-grade bituminous variety. The total tonnage is estimated at 123,000,000 tons, of which 60,000,000 is extractable. The Miocene series contains considerable quantities of brown and lignitic coal.

H. R. B.

The Squantum Tillite. By ROBERT W. SAYLES. Bull. Mus. Comp. Anat., Harvard College, LVI, No. 2 (1914), 141–75, pls. 12.

For many years the origin of the Roxbury conglomerate has been a subject of debate. As early as 1875 W. W. Dodge stated his belief in the glacial origin of these beds; the writer has at last established this view. The Roxbury series, comprising the Roxbury conglomerate, the Squantum tillite, and the Cambridge slate, is of late Paleozoic age, probably Permian. If there is no duplication of beds by folding, the tillite is 600 feet thick. It is an unstratified mass of unassorted materials much affected by dynamic movements, with the development of secondary cleavage. The rock fragments are of several kinds, variable in size, and mostly angular or subangular in shape. Striated stones were found at four localities.

The character of the included rock fragments suggests that the ice moved from the southeast. Intercalated slate beds indicate recessions of the ice. Whether they represent temporary retreats or long interglacial epochs is not known. Two conglomeratic beds below the principal tillite are of probable glacial origin, though it is not certain that they were deposited directly by the ice. H. R. B.

Geology of the Lake Pleasant Quadrangle, Hamilton Co., N.Y. By WILLIAM J. MILLER. New York State Museum, Bull. No. 182, 1916. Pp. 75, pls. 10, figs. 4, map 1.

The Lake Pleasant Quadrangle lies in the south central Adirondacks. The Grenville series of meta-sediments and intrusives outcrops over most of the region and is cut by a network of normal faults. Two small areas of Paleozoic strata are preserved by the dropping of fault blocks. The maximum thickness of this section is 500 feet. The formations preserved are: Potsdam sandstone, Theresa beds, Little Falls dolomite, Black River (Lowville) limestone, Trenton limestone, and Canajoharie (Trenton) shale.

The normal syenites of the region grade into basic syenites, also into granitic syenites and granites. The basic phases are attributed to the assimilation of dark Grenville gneisses. Pure differentiation has been the principal factor in the production of the silicic phases. Transitions from gabbro into basic syenite are described as due to assimilation by the gabbro. H. R. B.

Geology and Underground Waters of the Northern Llano Estacado. By CHARLES L. BAKER. Bull. Univ. Texas, No. 57, 1915. Pp. 225, pls. 10, maps 3.

For half a century or more the Llano Estacado has been famous for its stock-raising. Recently there has been a serious attempt to utilize the ground water for purposes of irrigation. The supply of shallow water is found to be insufficient to irrigate all the land that it underlies. Conservation is therefore of first importance, but unless dry farming proves more successful than in the past this region will always be chiefly a stockman's country.

Previous geologic work is largely confirmed by the present study. The strata represented are the Permian red-beds, the Upper Triassic Dockum group, comprising the Tecovas and Trujillo formations, marine beds of upper Comanchean age, possibly some Cretaceous rocks, and imperfectly known Miocene and later Cenozoics. H. R. B.

Petroleum and Natural Gas in Oklahoma. By C. W. SHANNON and L. E. TROUT. Okla. Geol. Surv., Bull. No. 19, Part I, 1915. Pp. 133, pls. 7, figs. 4.

The great public demand for information concerning oil and gas necessitates the publication, not only of detailed reports on individual fields, but also of papers containing general information regarding the oil and gas business. The present bulletin is designed to meet both demands. It is published in two parts. Part I deals with the general phases of the industry, and includes a short discussion of the geology of Oklahoma. Part II gives a more detailed account by counties of the oil and gas fields of the state.

H. R. B.

The Willow Creek District, Alaska. By S. R. CAPPS. U.S. Geol. Surv., Bull. No. 607, 1915. Pp. 86, pls. 15, figs. 5.

An area of 90 square miles at the head of the Little Susitna River, which enters Cook Inlet from the north, is described. The geologic formations are pre-Jurassic mica schists cut by quartzdiorites, and an Eocene sedimentary series with interbedded basaltic lava flows. Alaskite dikes and gabbro masses occur in association with the larger intrusives. Gold occurs in placers and quartz lodes. The latter are quartz-filled fissures in the quartz-diorite carrying free gold and sulphides.

H. R. B.

The Broad Pass Region, Alaska. By FRED A. MOFFIT. U.S. Geol. Surv., Bull. No. 608, 1915. Pp. 80, pls. 8, figs. 3.

The Broad Pass region comprises an area of about 3,700 square miles along and south of the axis of the Alaska Range east of Mount McKinley. The oldest rocks are of Devonian age, representing the same general horizon as the Devonian of the Mount McKinley and Porcupine River regions. The Mesozoics are less deformed than the Devonian series. Basic lava flows are apparently overlain by upper Triassic slates which are probably equivalent to the "undifferentiated Paleozoic" series of slates and graywackes along the south flank of the Alaska Range, as described by Brooks, Capps, and Eldridge. A series of slate, graywacke, and conglomerate is provisionally assigned to the Jurassic. At some time before the Tertiary these rocks were folded and intruded by igneous masses. The Eocene is represented by the Cantwell formation, in places intensely folded and cut by granites and diorites. The sections on Quaternary deposits, igneous rocks, and glaciation are by Joseph E. Pogue.

H. R. B.

Geology and Oil Resources of the West Border of the San Joaquin Valley North of Coalinga, California. By ROBERT ANDERSON and ROBERT W. PACK. U.S. Geol. Surv., Bull. No. 603, 1915. Pp. 220, pls. 14, figs. 5.

The region described in this bulletin is a strip 8 to 20 miles wide and 130 miles long lying along the east flank of the Diablo Range and the adjacent western edge of the San Joaquin plain. This foothill belt was studied with a view to determining whether or not oil fields exist, as in the Coalinga and other districts farther south. In so far as finding new oil fields is concerned, the examination proved disappointing. Organic shales were found in great quantity, but there are few spur folds running out toward the valley. The presence of oil pools to the south is determined by such folds.

The oldest rocks in the Diablo Range belong to the Franciscan formation, of supposed Jurassic age, which is separated from the oldest Cretaceous rocks by a great unconformity. The Knoxville group (Comanche) is believed to be absent. The Chico (Cretaceous) is represented by the Panoche and Moreno formations, marine shales and sandstones that reach the enormous thickness of 24,000 feet. The Moreno, composed largely of organic remains such as diatoms and foraminifers, has been referred by some authors to the Tertiary, but it is now found to contain Cretaceous fossils. Hitherto strata of this type have been known in California only in the Tertiary.

The Martinez (lower Eocene) is present only in the southern part of the area, where it is represented by 5,000 feet of marine beds. The Tejon (upper Eocene) is present throughout the region, varying in thickness from 50 to 2,200 feet. The Oligocene is represented by the Kreyenhagen diatomaceous shale, with unconformities above and below. In the southern part of this belt the Miocene is represented, as in the Coalinga district, by the Vaqueros, Santa Margarita, and Etchegoin-Jacolitos formations, with a maximum thickness of 5,000 feet, each separated from the next adjoining by an unconformity. The Big Blue serpentine, formerly considered to represent the lower part of the Santa Margarita, contains typical Vaqueros fossils. Farther north the lower and middle Miocene were not differentiated. The San Pablo is equivalent in part at least to the Etchegoin-Jacolitos. Post-Miocene beds up to 2,200 feet thick are tentatively correlated with the Tulare formation.

The local factors influencing the accumulation of oil, evidences of oil in the region, and the future possibilities of development are dis-

cussed in detail. The oil is believed to have been derived from the two organic shales, and apparently each gave rise to a different type of oil—the Moreno to a light paraffin oil and the Kreyenhagen to a heavy asphalt oil. The diatoms are believed to have been the greatest contributors in the formation of the oil.

H. R. B.

Mineral Resources of Alaska for 1914. By ALFRED H. BROOKS and Others. U.S. Geol. Surv., Bull. No. 622, 1915. Pp. 380, pls. 11, figs. 8.

This volume is the eleventh of a series of annual bulletins summarizing the results of the investigations of Alaskan mineral resources and the status of the industry in the territory. Fourteen papers deal with the mineral resources of certain districts.

The gold and copper deposits of the Port Valdez district are descibed by B. L. Johnson. The country rock includes basic lavas, slates, graywackes, and other sediments of Mesozoic age. Gold occurs in quartz-filled fissure veins formed at moderate depths; the copper chiefly as sulphide impregnations and replacements of sheared zones along the fractures. The mineral association in both gold and silver ores is practically the same, varying only in relative proportions. The sulphide minerals are pyrite, chalcopyrite, galena, sphalerite, and some pyrrhotite and arsenopyrite. There was but one period of mineralization. As in the Ellamar district, both types had a common origin in solutions that circulated subsequent to late Mesozoic intrusions, with which they were probably genetically related.

P. S. Smith and A. G. Maddren describe the quicksilver prospects of the Kuskokwin region. The ore occurs in brecciated zones in Cretaceous sandstones and shales at the contacts of granitic and andesite dikes. Cinnabar, generally with stibnite, occurs in quartz veinlets and stringers. In places calcite and siderite are present. Some cinnabar has also been obtained from placer gravels, and detritus in a stream near one of the deposits contains native mercury.

H. R. B.

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—WILLIAMS, M. Y. An Eurypterid Horizon in the Niagara Formation of Ontario. [Canada Department of Mines, Museum Bulletin No. 20, No. 1574, Geological Survey, Geological Series, No. 29. Ottawa, October 8, 1915.]

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